



Review

Potential impacts of climate change on vegetable production and product quality – A review

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ABSTRACT

This paper reviews climate change impacts on the production, physiology, yield, and product quality of vegetables affected by shifting CO₂ and O₃ concentrations, precipitation and temperature conditions, as well as subjected to extreme weather events. The emphasis is on the temperate cool climate of Western Europe. Physiological processes such as respiration and photosynthesis can acclimate to increasing atmospheric CO₂ and temperatures. The effect of increased CO₂ on vegetables is mostly beneficial for production, but may alter internal product quality, or result in photosynthetic down-regulation. Heat stress reduces fruit set of fruiting vegetables, and speeds up development of determinate vegetables, shortening their time for photoassimilation. In both cases, yield losses result with an impaired product quality, thereby increasing production waste. A longer growing season, arising from warmer temperatures, allows a greater number of plantings to be cultivated, contributing to greater annual yields. However, some vegetables need a period of cold accumulation to produce a harvest. Despite the increasing potential for winter cultivation in the future, perennials like asparagus might increasingly suffer from a lack of winter chilling. In cauliflower, higher temperatures will likely cause insufficient vernalization delaying head induction.

This review may contribute in improving the adaptation strategies of vegetable production to climate change for a sustainable horticulture due to an effective risk management by meeting the problems of possible waste increase; breeding of new heat, drought and pest tolerant cultivars; secure water resources; increase the use of renewable energy sources; stimulating new ideas in innovative technologies; development of new approaches to secure stable yields and improve the product quality of vegetables for a cleaner production. © Elsevier. All rights reserved.

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1. Introduction

With the onset of the industrial revolution in the 18th and 19th century, changes in weather and climate have been observed, subsequently leading to an increase in climate research and the development of climate modeling techniques (IPCC, 2000). Today, scientists agree that the main driving force behind these changes is overwhelmingly of an anthropogenic origin. According to the Intergovernmental Panel on Climate Change (IPCC), the combustion of fossil energy sources and the associated emissions of greenhouse gases (GHG), e.g. CO₂, N₂O, CH₄, cause an accumulation of the latter in the atmosphere (IPCC, 2013). Changes in the atmospheric concentrations of GHGs, with the ability to absorb infrared radiation reflected from the earth's surface, may alter the energy balance of our climate system, causing the atmosphere to warm (IPCC, 2013). In the frame of the COP21 conference in Paris, governments decided to reduce the use of fossil fuels with the ambition of a complete waiver at the end of the century, thereby trying to limit global warming to or below a 2 °C increase. These efforts send out clear signals, however, with an unclear outcome. With vegetable production being among the sectors directly depending on climate and weather conditions, studying potential adverse impacts becomes a priority. However, the magnitude of change cannot be predicted with certainty.

With ca. 3.2 Mt of fresh vegetables produced in 2013, on an area of 112,229 ha, vegetable production is a viable and growing part of horticulture in Germany and deserves to be investigated in the light of climate change. Food quality demands by the consumers and trade are on the increase and must be fulfilled by growers, producing a nutritious, clean, fresh, and high quality product. This is cumbered by the fact that weather conditions cannot be controlled and plant exposure to stressful environments with subsequent reductions in product quality are often unavoidable. Agricultural practices like greenhouse production can help to become partly independent from weather conditions, but only to a certain degree. The challenges that climate change brings along will require adaptation strategies in order to meet consumer demands and to ensure high food security standards. The majority of climate change

studies are on forest and fruit trees, e.g. Luedeling et al. (2013a, 2013b), but rarely on short-lived vegetables. Hence, the few reviews of climate change impact on vegetables concentrate on tropical and subtropical regions and are provided by De la Peña and Hughes (2007), Ayyogari et al. (2014), and Mattos et al. (2014). To the best of our knowledge, no reviews have been conducted regarding the effects of climate change on vegetable production in temperate cool European climates. The objective is therefore to review the recent findings on the topic of future climate projection, and to put this into the context of vegetable production to better assess the potential impact on plant performance, yield, and product quality. Adaptation possibilities are presented, which may ensure sustainable and resilient vegetable production. Without claiming to cover all the aspects affecting this topic, we focus on the main parameters regarding the European region, and Germany in particular.

2. Methodology

The focus of this study is the production, physiology and product quality of fresh vegetables excluding potatoes, affected by recent/future climate change, as well as on possibilities for adaptation. Mitigation issues are outside the scope of this paper, although we acknowledge the importance of the topic. A systematic literature review was conducted, examining published articles from 1990 to 2017. However, little research has been dealing with the effect of climate change on vegetable crops. Therefore, we expanded our search to include less recent literature as well. The review is based on literature from temperate regions of the Northern hemisphere, including the Mediterranean basin as a possible indicator of more intense heat waves and milder winters in the near future. To the best of our knowledge, no reviews have been conducted regarding the effects of climate change on vegetable production in temperate European climates until now. Even in a scientometric study, recently published by Alexandre-Benavent et al. (2017), concerning trends in scientific research on climate change effects in agriculture and forestry (2005–2014), we found no information for vegetables. The literature search was conducted using the following

academic databases: Web of knowledge, Scopus and ScienceDirect, ResearchGate, Google Scholar, and Hortigat (in German). Several keywords were chosen to obtain a wide number of search results. Keywords were selected after identifying the common climate change issues dealt with by scientists in the field of cereal grain production and other common crops. The keywords selected were: “climate change”, “vegetable production”; “climate change”, “vegetable(s)”, “product quality”, “climate change”, “vegetable(s)”, “waste”; “impacts of climate change”, “horticulture”; “vegetable”, “FACE”; “adaptation climate change”, “agriculture”; “climate change”, “greenhouse production”; “heat waves”, “vegetable(s)”; “mild winter”, “vegetables”; “climate change”, “vegetable physiology”; “vegetables”, “high temperatures”; “climate change”, “vernalization vegetable(s)”. All terms were searched in combinations with AND, e.g. “climate change” and “vegetables”. The same keywords were used replacing the word “vegetables” with the respective vegetable name (e.g. “heat waves” AND “tomato”, ...). All keywords were searched in German as well. The literature included mainly peer-reviewed articles, but sometimes also a few studies in technical journals, books, and conference proceedings. Titles and abstracts from more than 3000 articles were screened and evaluated, before selecting relevant papers. We selected studies including topics on (1) the nature of climate change in temperate regions, (2) the reactions of several vegetable crops to environmental changes such as temperature, CO₂, and water availability, (3) adaptation strategies to potential climate changes, and (4) reduction of waste in the production process and value chain of fresh vegetables. Climate change has been selected as the primary impact indicator.

3. Background: emission scenarios to representative concentration pathways

In 1988, the IPCC was established and has become the most important interdisciplinary institution to deal with climate change issues, from scientific basics to assessments of vulnerability and mitigation on a global scale. The Special Report on Emissions Scenarios (SRES) in 2000 became widely accepted and describes a range of possible future GHG emissions, concentrations and their consequences such as temperature rise until the year 2100, depending on human behavior and development in terms of technology, economy and demography (IPCC, 2000). In the SRES storylines, B1 is considered as moderate, A1B and B2 as relatively

balanced whereas the A1 family, especially A1F1 scenario constitutes a worst case scenario (Table 1). Due to the large number, the over 40 SRES scenarios have now been updated and replaced by the four Representative Concentration Pathways (RCPs), RCP8.5, RCP6.0, RCP4.5 and RCP2.6. The rise of CO₂ concentrations and projected changes in surface mean temperature under these scenarios, as described in the IPCC's Assessment Report 5 (AR5), are listed in Table 2. The objectives of a 2 °C warming limit, set during the COP21 conference, would correspond to the warming described by RCP2.6.

4. Physiological responses of vegetables to climate change

Physiological processes such as photosynthesis or respiration are mechanisms on the molecular scale that are involved in proper plant metabolism, organ development, synthesis of nutritious elements, and also in stress responses. Plant physiology is highly affected by increasing temperatures, carbon dioxide (CO₂) and ozone (O₃) concentrations, but vegetables can also acclimate to these new conditions.

4.1. Elevated CO₂

Vegetable dry matter consists of 40–45% carbon and ultimately derives from CO₂ as the only source of plant photosynthesis and an indispensable part of the Calvin-Benson cycle. During the course of

Table 2
Representative concentration pathways and future projections.

Scenario	Year	Mean T rise ^a (relative to 1986–2005)		Future CO ₂ concentrations in ppm	
		2050	2100	2050	2100
RCP 6.0		1.3 °C	2.2 °C	477 ^{b,c}	669 ^{b,c}
RCP 4.5		1.4 °C	1.8 °C	486 ^d	538 ^d
RCP 2.6		1 °C	1 °C	442 ^e	420 ^e
RCP 8.5		2 °C	3.7 °C	540 ^f	935 ^f

RCP = Representative concentration pathways.

^a IPCC (2013).

^b Fujino et al. (2006).

^c Hijikata et al., (2008).

^d Clarke et al. (2007).

^e van Vuuren et al., (2007).

^f Riahi and Nakicenovic (2007).

Table 1
SRES climate scenarios and future temperature projections.

Family ^a	Storyline ^a demographic, socio-economic and technological considerations	Scenarios ^a	Temperature rise ^b (2090–2099 relative to 1980–1999)
A1	convergent world very rapid economic growth rapid technological development global population peaks in mid-century and declines thereafter	A1F: fossil fuel intense	4.0 °C
		A1B: balanced	2.8 °C
		A1T: no fossil fuels	2.4 °C
A2	Heterogeneous world, with local identities Slow economic growth, high regionality Technological development is slow Continuously increasing global population	A2	3.4 °C
B1	Convergent, globalized world Rapid changes in economic structures Clean and resource-efficient technologies Global population equal to A1	B1	1.8 °C
B2	Heterogeneous world, high regionality Intermediate economic development Less rapid and more diverse technological change than in B1 and A1 Continuously increasing global population at a rate lower than A2	B2	2.4 °C

The SRES Scenarios (A1, A2, B1, B2), are characterized by their storyline which is decisive for their family affiliation. Scenarios are named identically to their family.

^a IPCC (2000).

^b IPCC (2007).

the current century, atmospheric CO₂ levels are assumed to progressively rise, and the extent depends on the prevailing scenario, with 935 ppm at the end of the century being the upper limit (Table 2).

4.1.1. C₃ versus C₄ plants

The two most widely spread plant mechanisms of CO₂ fixation during photosynthesis are the C₃ and the C₄ pathway. The main differences concern not only the catalysing enzymes and intermediate metabolic products, but is also expressed in the leaf anatomy.

Most vegetables are C₃ species, where CO₂ is assimilated by Ribulose-1,5-bisphosphate (RuBP) and catalyzed by RuBP carboxylase/oxygenase (Rubisco). The reaction products are two molecules of 3-phosphoglycerate, a three carbon molecule and hence named C₃. This chain of successive reactions is known as the Calvin-Benson cycle. However, Rubisco can also act as oxygenase, by assimilating O₂ in a light dependent reaction producing CO₂. This unproductive process is known as photorespiration and thought to be a nature adaption mechanism to changing oxygen concentrations (Edwards and Walker, 1983).

By contrast, few vegetable crops such as sweet corn, use the C₄ pathway, in which CO₂ is first assimilated to Phosphoenolpyruvate (PEP), resulting in the formation of malate or aspartate, which are four carbon molecules and hence named C₄ (Taiz and Zeiger, 2014). This reaction is catalyzed by PEP carboxylase/carboxykinase, which lacks an oxygenase reaction and has a greater affinity to CO₂ (Blanke et al., 1987). In C₄ species, leaf anatomy is characterized by a spatial segregation of light and dark reactions of photosynthesis. This anatomical setup, where the Calvin-Benson cycle is located in cells surrounding the bundle sheath, is named Kranz anatomy. In these cells, the C₄ molecule releases the CO₂ initially fixed there, which enables higher concentrations around Rubisco. Because of this elegant CO₂ concentrating mechanism and the lack of oxygenation by PEP carboxylase/carboxykinase, C₄ photosynthesis is considered more efficient than C₃ photosynthesis (Edwards and Walker, 1983).

4.1.2. The benefits of CO₂ enrichment

Increased CO₂ concentrations can stimulate photosynthesis particularly of C₃ plants, since C₃ photosynthesis is limited by CO₂ at current atmospheric concentrations. Thereby, climate change might contribute to higher yields in vegetable plants. CO₂ enrichment to 600–1000 ppm CO₂ is a common practice in greenhouses. The higher CO₂ level diffuses through the stomata to the chloroplast, where Rubisco facilitates carboxylation, and reduces oxygenation hence photorespiration. Thereby, yield of celery, Chinese cabbage, leaf and stem lettuce increased more than twofold when grown at CO₂ concentrations around 800–1000 ppm (Jin et al., 2009). In onion grown at 700 ppm, shoot and root dry matter was increased by elevated CO₂, when compared to 360 ppm

(Bettoni et al., 2014). In tomato, cucumber and lettuce, yields increased by up to 44% when atmospheric CO₂ doubled (Korres et al., 2016). However, CO₂ concentrations of 1000 to 1200 ppm, especially in field grown vegetables, are in excess of the expected ambient CO₂ values.

Free Air Carbon dioxide Enrichment (FACE) is a method of providing experimental field plots with CO₂ (Fig. 1). These growing conditions are closer to field conditions than those in enclosed environments. In such a FACE plot, Burkey et al. (2012) found French bean yields enhanced by 35% when exposed to 550 ppm compared with ambient CO₂ (378 ppm). Butterly et al. (2016) showed that shoot growth and biomass production of field pea was enhanced at 550 ppm, while the elevated CO₂ levels alleviated the inhibitory effects of high soil N on nodulation and N₂ fixation. But also FACE apparatuses are limited, because CO₂ concentrations over 600 ppm are only possible through high monetary expenses (Da Matta et al., 2009). Thus environments as described in high emission scenarios (RCP8.5 and A1F1) can only hardly be replicated while the temperature target values within the 2 °C limit are covered.

Even though the majority of studies on CO₂ enrichment in vegetables suggest a photosynthesis, biomass, and yield increase, it is not always beneficial, e.g. when other factors like light, nutrients, or water are limiting (Reich et al., 2015). Tartachnyk and Blanke (2007) showed such negative effects on young tomato plants due to photoinhibition at high CO₂ during early spring, when plants are adapted to insufficient light while solar radiation rises.

In C₄ plants, photosynthesis is thought to be CO₂-saturated at current concentrations and thus not expected to benefit from changes in the atmospheric levels. This was shown in a FACE study by Ruiz-Vera et al. (2015) in maize grown at 390 ppm and 585 ppm. Photosynthesis remained unchanged regardless of CO₂ concentrations; biomass and yield were not stimulated. In C₄ crops, photosynthesis and yield might, however, be enhanced indirectly through several factors like a higher growth potential, declining water use, and reduced drought stress (Leakey et al., 2009).

4.1.3. Elevated CO₂ affects stomatal conductance, WUE and evaporative cooling

As a result of elevated CO₂, stomatal conductance and transpiration are decreased in most vegetables regardless of crops being C₃ or C₄ species (Leakey et al., 2009; Da Matta et al., 2009). Radoglou et al. (1992) observed that stomatal conductance in common bean (*Phaseolus vulgaris* L.) was reduced by 40% at 700 ppm compared to ambient (350 ppm CO₂) with both high and low nutrient supply in open top chambers (OTCs). The CO₂ assimilation increased by 40% at low and 30% at high nutrient supply. In carrot, Kyei-Boahen et al. (2003) reported that stomatal conductance decreased by 17% when grown at 650 ppm and by 53% at 1050 ppm CO₂ in a controlled environment (CE) chamber (control: 350 ppm). CO₂ assimilation



Fig. 1. Free Air Carbon dioxide Enrichment (FACE) was introduced in the early 90s, where CO₂ is released through circular tubes in the field and enriches the atmosphere of the surrounded plants, here cucumbers at the FACE equipment of University Geisenheim, Germany (Photo: Gruda, private collection).

increased by 43% (650 ppm) and by 52% (1050 ppm). In conclusion, these case studies with bean and carrot as prime examples have shown a concomitant decrease in stomatal conductance viz transpiration under elevated CO_2 across vegetable species and a possible increase in photosynthesis (Fig. 2).

The combination of less transpiration and greater photosynthetic rates at high CO_2 , improves the water use efficiency (WUE), defined as the ratio of carbon uptake to water loss (Ziska and Bunce, 2006). Goudriaan and Bijlsma (1987) observed this increase in Faba bean (*Vicia faba* L.) at 700 ppm and Radoglou et al. (1992) for common bean seedlings (*Phaseolus vulgaris* L.); the curve for WUE as function of CO_2 concentration was positively linear. In carrot, transpiration was reduced by 15% and WUE increased by 76% at 650 ppm compared to a 350 ppm treatment (Kyei-Boahen et al., 2003).

Transpiration also provides effective evaporative cooling (Solomakhin and Blanke, 2010), which may be reduced at partial stomatal closure due to high CO_2 and may cause leaf temperatures of vegetables to increase (Da Matta et al., 2009); for other crops this cooling was calculated up to 1.6 °C under open field conditions (Solomakhin and Blanke, 2010). Thus, elevated CO_2 might reduce water use, but may make some vegetables more vulnerable to heat stress in hot spells (Fig. 2).

By contrast, stomatal conductance in cucumber was not changed, even at atmospheric levels of 1200 ppm CO_2 (Agüera et al., 2006), while that of some radish cultivars was increased after long-term exposure to 650 ppm CO_2 (Choi et al., 2011) showing the diverse reactions of vegetable crops.

4.1.4. Photosynthetic acclimation after long-term exposure to elevated CO_2

Some of the above conclusions were derived from short-term exposure to high CO_2 levels. However, in the long term, plants adapt by scaling down their photosynthetic mechanisms in a process known as photosynthetic acclimation or down-regulation (Ziska and Bunce, 2006), as observed in monoecious cucumber (*Cucumis sativus* L. cv. 'Chipper') by Peet (1986). After only 16 days of exposure to 1000 ppm CO_2 in a growth chamber, net assimilation rates and relative growth rates decreased continuously, similar to Sánchez-Guerrero et al. (2005), who observed reduced biomass gains in late growing stages at 700 ppm due to photosynthetic acclimation in cucumber. Sage et al. (1989) found that cabbage (*Brassica oleracea* L.), French bean (*Phaseolus vulgaris* L.) and eggplant (*Solanum melongata* L.) differed in their acclimation response to long-term CO_2 exposure of 28 days in a greenhouse (control: 300 ppm; enriched: 900–1000 ppm); all of them reduced Rubisco activity and growth. Cabbage showed the strongest down-

regulation of photosynthesis, whereas the magnitude of acclimation was lower in French bean, as generally reported for leguminous species (Butterly et al., 2016). Nonetheless, in the reviews of FACE experiments by Bagley et al. (2015) and Leakey et al. (2009), the gains of elevated CO_2 outweighed the negative effects of acclimation, as carbon uptake was shown to increase at a rate of 13% in C_3 crops, 21% in shrubs and 19% in legumes, which both did not include vegetable crops.

4.1.5. Elevated CO_2 affects dark respiration

Plants produce ATP through the oxidation of reduced sugars built during photosynthesis and use it for maintenance and development processes (Taiz and Zeiger, 2014). This process of metabolising valuable photosynthates is known as respiration and is involved in stress responses hence increases, when exposed to unfavorable conditions. Respiration should preferably be as low as possible and a high photosynthesis/respiration ratio favors good yields so that daytime photosynthesis should exceed dark respiration at night; at 15 °C, this ratio usually exceeds 10 (Moretti et al., 2010; Mattos et al., 2014). Peet and Wolfe (2000) explained that root and leaf dark respiration of tomatoes, lettuce, peppers, peas, and maize plants, declined very rapidly when the air was enriched with CO_2 at night. In future scenarios vegetable plants will be growing at elevated CO_2 , particularly at night, leading to the assumption that night time respiration will be lower, thereby increasing the photosynthesis/respiration ratio, especially when daytime photosynthesis is stimulated (Peet and Wolfe, 2000; Mattos et al., 2014). However, in French beans, such an effect was absent, when grown at elevated CO_2 (Jahnke, 2001) thus nocturnal respiratory inhibition might not occur in all species.

By contrast, in some species, e.g. soybean, respiration may as well increase (Leakey et al., 2009), or slow growth (Ziska and Bunce, 2006). In conclusion, the diverse and sometimes contradictory results, indicate that the area of respiration responses at high CO_2 needs more research. The latter should include a large range of vegetable plants in order to determine how the photosynthesis/respiration ratio and yields are affected under climate change conditions in the respective species.

4.2. Elevated temperatures

Air temperature is a predominant environmental factor for vegetable growth and yield. Vegetable crops have species specific temperature requirements. The temperature optimum for hot season vegetables is between 25 and 27 °C, warm season crops and cool/hot season crops between 20 and 25 °C, and cool/warm season crops (cold season crops) between 18 and 25 °C (Wien, 1997).

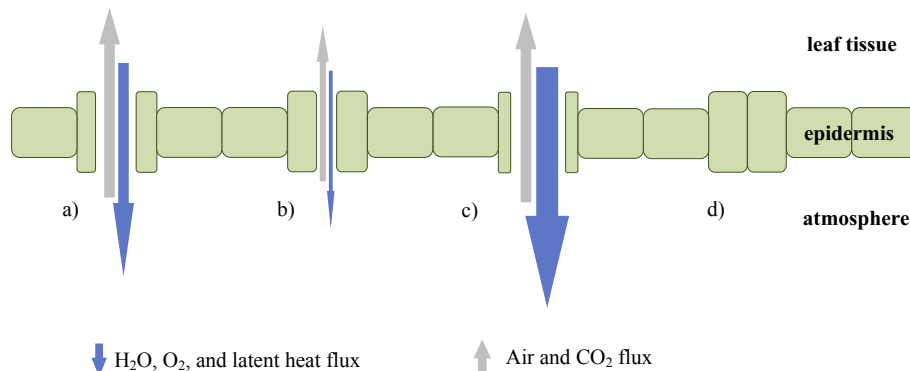


Fig. 2. Schematic representation of the lower epidermal leaf boundary with stomata and their interaction with CO_2 and temperature. a) Control (400 ppm CO_2): Normal stomatal opening, gas exchange rate and water use efficiency (WUE). b) 500–900 ppm CO_2 : Partial stomatal closure and reduced gas exchange result in better WUE and reduced evaporative cooling. c) High temperature and water supply: Stomatal opening for excessive transpirative cooling results in decreased WUE. d) High temperature and drought: Stomatal closure to reduce transpiration losses and maintain water status.

Global warming is expected to increase both the mean temperature and temperature extremes in the future, thereby changing the growing conditions for vegetables (Table 1, Table 2).

4.2.1. Elevated temperatures affect photosynthesis and respiration

The temperature optimum of 20–32 °C for C₃ crops, such as most vegetables, in terms of maximum photosynthesis (Wien, 1997) is exceeded by that in C₄ crops, e.g. 34 °C in sweet corn (Ruiz-Vera et al., 2015). Plant response to elevated temperature is not only species specific, but depends also on growth stage and plant age. Ben-Asher et al. (2008), grew sweet corn in CE and found large photosynthetic rates of young seedlings at 25/20 °C (day/night), while above 30/25 °C photosynthesis was reduced by 30–60%. Later, when fully-grown, photosynthesis at 25/20 °C decreased, while that of the 30/25 °C plants increased and came to a complete standstill in the 40/35 °C treatment. When Ruiz-Vera et al. (2015) grew maize in the field at elevated temperatures of only 25.4 ± 1.6 °C, they however observed a 5% decrease in photosynthesis compared to unheated control (22.7 ± 1.6 °C). Despite increased biomass production, seed yield decreased by 14%. In response to temperature stress, plants can shift their thermal optimum, so that they can perform more efficiently (Körner, 2006). Spinach plants, raised in growth chambers at 15/10 °C or 30/25 °C until reaching leaf 7, were exposed to a temperature rise from 9 to 39 °C (Yamori et al., 2005). Plants raised at 30/25 °C, had a higher optimum temperature for photosynthesis, and showed greater photosynthetic rates at their optimum than when raised at 15/10 °C. Despite that, C₃ leaves can generally maintain photosynthetic rates within 80% of their maximum over a large temperature span (Körner, 2006).

Carbon assimilation is a balance between two opposite mechanisms, the CO₂ fixation by Rubisco and the CO₂ release by respiration and photorespiration (Edwards and Walker, 1983). Since respiration rates increase between 0 and 30 °C, and high temperatures promote photorespiration (Taiz and Zeiger, 2014), above optimum conditions for vegetable growth stimulate respiration while decreasing photosynthesis, thereby negatively affecting the ratio between both. But even if temperature rises to heat stress conditions, plants may acclimate and maintain respiration at minimum rates (Körner, 2006). For instance, spinach plants raised at 15/10 °C, showed higher respiration rates than those raised at 30/25 °C, in all temperature treatments (Yamori et al., 2005).

4.2.2. Elevated temperatures increase growth rate

Most vegetables as C₃ plants grow better when temperatures increase, but do not exceed ca. 25 °C (Peet and Wolfe, 2000). By contrast, in sweet corn as a C₄ plant, growth rates increase linearly between 10 °C and 30 °C (Wien, 1997). In a meta-analysis including 127 publications, Lin et al. (2010) showed that global warming significantly increased biomass by an averaged 12.3% across all terrestrial plants examined; in their classification into plant

functional types (PFT's), the category of herbaceous plants is most suitable for vegetable crops with an increase of 5.2% in biomass. Elevated temperatures, however, benefit plants only as long as they do not exceed critical thresholds, e.g. during heat waves, resulting in stress responses on the physiological level that might express in diminished yields and quality.

4.2.3. Elevated temperatures increase transpiration

With increasing temperatures, plants often increase their transpiration rates due to large water vapor gradients and the need for cooling, provided sufficient water supply. In the C₄ sweet corn, Ben-Asher et al. (2008) observed greatest transpiration rates, and hence unnecessary water loss, at 40/35 °C, which contributed to a significantly decreased WUE (Fig. 2). The typical C₃ vegetables reduce such losses by closing their stomata with the consequent decrease in photosynthesis, especially when combined with drought (Gruda and Tanny, 2014).

4.3. Interactions of elevated temperature and CO₂ with yield production

Vegetables react to a rise of both, CO₂ and temperature, and their interaction, as a result of climate change (Führer, 2003; Da Matta et al., 2009; Choi et al., 2011; Reich et al., 2015). Growth stimulation by elevated CO₂ generally becomes greater when temperature rises concomitantly, as both factors are positively correlated. Conversely, elevating CO₂ in vegetables can reduce heat stress, but only under otherwise optimum conditions such as ample water supply, light intensity, nutrient supply etc. If one of the latter is inadequate, plant growth and yield become limited by this factor, a plant behavior described in the minimum law of Liebig. For the C₃ soybean, a rise in atmospheric CO₂ increased the photosynthetic thermal optimum shift towards higher temperatures and yielded larger photosynthesis alongside an alleviation of photosynthetic acclimation (Bagley et al., 2015). However, in some species, e.g. French bean, 700 ppm CO₂ was not able to relieve the negative effects, irrespective of temperatures between 40/30 °C and 28/18 °C (Prasad et al., 2002).

The positive interaction between temperature and elevated CO₂ has been demonstrated for both tuber and leaf development (Table 3). In onion, grown at different temperatures of 12–19 °C, increasing CO₂ up to 532 ppm resulted in enhanced yields at all temperatures (Daymond et al., 1997). Chinese cabbage assimilated 36% more leaf biomass at a combination of high CO₂ (800 ppm ± 100 ppm compared to 420 ppm ± 30 ppm) and temperature (21/18 °C day night compared to 15/12 °C, i.e. 6 °C difference), with a concomitant 18% increase in net assimilation (Reich et al., 2015). By contrast, Choi et al. (2011), found that leaf dry weight of Chinese cabbage was decreased in all cultivars after 90 days of growth at 650 ppm CO₂ and a temperature of 4 °C above ambient with a decrease in photosynthesis. In the same study,

Table 3
Vegetable response to high CO₂ and temperature.

Crop	Parameter		CO ₂ concentration	Temperature	Reference
Chinese cabbage	Yield	↑	800 ppm	21/18 °C	Reich et al. (2015)
	Stomata opening	↑			Reich et al. (2015)
Onion	Yield plant development	↓	650 ppm	Ambient + 4 °C	Choi et al. (2011)
		↑	532 ppm	12–19 °C	Daymond et al. (1997)
		=			
French bean	Seed yield	↑	350–750 ppm	14.5–18.5 °C	Wurr et al. (2000)
		↓	700 ppm	28/18 Yield = 0 at 37/27	Prasad et al. (2002)
Maize	Photosynthesis	↓	585 ppm	25.4 ± 1.6 °C	Ruiz-Vera et al. (2015)
	Yield	↓			

Table 4
High O₃ damages and effects on vegetable physiology.

Variable	Effect	Observed in	Reference
Photosynthesis	=	broccoli	De Bock et al. (2012)
	↓	French bean	Flowers et al. (2007)
Biomass production	↓	Tomato	Oshima et al. (1975)
	=	broccoli	Vandermeiren et al. (2012)
	↓	lettuce, radish, cucumber	Temple et al. (1986); Beckerson and Hofstra (1979)
Yield	↓	French bean, spinach, tomato, turnip, lettuce, radish, cucumber, onion, melon, maize, broccoli	Oshima et al. (1975); Beckerson and Hofstra (1979); Temple et al. (1986); Burkey et al. (2012); Calvo et al. (2007);
Leaf chlorosis	↑	tomato, lettuce, radish, cucumber	Beckerson and Hofstra (1979); Calvo et al. (2007); Temple et al. (1986)
Ripening time	↓	cucumber, tomato	Calvo et al. (2007); Temple et al. (1986)
Maturation time	↓	lettuce, radish	Beckerson and Hofstra (1979)

radish showed increased root dry weight at elevated temperature and CO₂, but magnitudes varied among cultivars and photosynthesis was higher only in one of the three.

However, according to Körner (2006), CO₂ stimulation decreases at temperatures outside the optimum range, particularly for reproductive organs: Prasad et al. (2002), subjected French beans to different temperature regimes (28/18; 31/21; 34/24; 37/27; 40/30 °C) and under two CO₂ concentrations (350 ppm and 700 ppm) in sunlit growth chambers. They found that when temperature increased from the lowest to the highest, the number of seeds per plant and seed yield decreased under both 350 ppm and 700 ppm CO₂; above 37/27 °C, no yield was produced in either CO₂ concentration. Similar results were obtained in the C₄ crop maize in a FACE facility at elevated temperatures (Ruiz-Vera et al., 2015), where photosynthesis declined and yields were lower at both 390 and 585 ppm. These results show that CO₂ might only alleviate the negative effects of high temperature until a certain threshold, with the exception of legumes and C₄ crops with CO₂ concentration mechanism and negligible effects of CO₂ increase.

The foregoing chapters showed that transpiration is highly affected by both, increasing temperatures and CO₂. Blossom end rot (BER) and tipburn are physiological disorders of various vegetables, e.g. of *Solanaceae* fruit, related to excessive leaf transpiration and disturbed Ca translocation in the transpiration stream in the xylem (Saure, 1998). The effect of climate change brings about a discrepancy between higher temperature associated with increased transpiration but reduced transpiration due to elevated CO₂ resulting in opposing effects on the occurrence of these two physiological disorders.

4.4. Effects of elevated atmospheric ozone on vegetables

Ozone in the lower atmosphere is considered both, a toxic air pollutant for plants and a greenhouse gas, and ambient ozone levels have doubled since the industrial revolution (Booker et al., 2009). Summer smog consists mainly of O₃ and forms under high temperatures, intense irradiation, as well as at elevated atmospheric amounts of reactive nitrogen species and volatile organic compounds (Mauzerall and Wang, 2001; Mattos et al., 2014).

After ozone uptake by plants through the stomata, the toxicity originates from highly oxidative processes, which include the formation of free radicals harming cellular structures within the plant. This leads to visible symptoms such as premature leaf senescence as well as inhibited growth and photosynthesis (Table 4), the latter derived from reductions in both, activity and amount of Rubisco (Booker et al., 2009). Photosynthesis in common bean was reduced by 40% in O₃ sensitive cultivars (60 ppb O₃ for 12 h a day), with injuries and reduced pod yield (Flowers et al., 2007). In broccoli, elevated ozone (ambient + 40 ppb O₃; 8 h per day) did not decrease leaf photosynthesis (De Bock et al., 2012), and fresh weight was unchanged (Vandermeiren et al., 2012) indicating that ozone responses are concentration and species specific; glucosinolates (GLS) composition was altered with a considerable increase in protein

content. Along the protein content, ozone also increased the lipid content of common bean (Wang and Frei, 2011).

Leaf foliage was damaged and ripening delayed in five tomato cultivars, grown at 50 ppb per hour in OTCs with a reduced fruit sugar content (Calvo et al., 2007). Fruit set at the early harvest was reduced while at the end of the season there was no significant yield loss. Under severe O₃ concentrations (200 and 350 ppb; 2.5 h, 3 days a week), Oshima et al. (1975) observed great reductions in biomass in tomato, reduced fruit set and hence reduced yield after several weeks. Lettuce, exposed to severely increased O₃ concentrations of 104 ppb or 128 ppb for a daily 7 h period developed intercostal chlorosis followed by necrosis before the leaf tissue collapsed; head weight was reduced by 13% for the lower concentration (104 ppb O₃) and 35% for the high concentration and plants matured two to three weeks later compared to lower treatments of 104 ppb O₃ (Temple et al., 1986). Beckerson and Hofstra (1979), reported foliar injuries in radish and cucumber similarly to those in lettuce.

Conclusively, elevated O₃ (≥40 ppb) levels induced leaf chlorosis and necrosis, a 5–10% yield reduction in spinach, bean, lettuce, onion, tomato, turnip (Booker et al., 2009), delayed fruit ripening, and reduced fruit sugar content as well as fewer fruits depending on time of exposure, developmental stage and ozone sensitivity of the plant; the C₄ species maize was less affected at ozone concentrations of 8.6–20 ppb.

These negative effects of high O₃ become less pronounced under enriched CO₂ (Fuhrer, 2003; Booker et al., 2009), possibly due to the greater antioxidant capacity and detoxification potential or more likely due to exclusion at high CO₂ (Fuhrer, 2003).

5. Impacts on vegetable production systems

Climate change will not only impact vegetable physiology, but will also affect the production systems they are grown in. Elevated temperatures in particular change the framework conditions by extending the growing season, altering the planning process and shifting input factors such as energy consumption.

5.1. Extended cultivation season under warmer spring and autumn

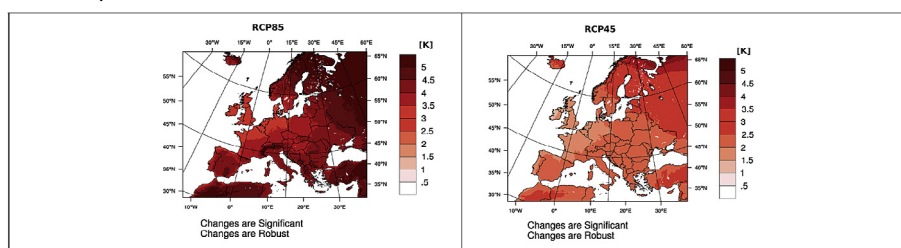
The thermal growing period, with temperatures above 5 °C, is the period with favorable growing conditions for early vegetables and marks the beginning and the end of the production season. From 1961 to 2005 it has extended by 35 days (Chmielewski, 2007), and future trends describe a further increase (BOX 1). With the aim to even further extend the growing season, and supply the market with vegetables at times of high product prices, plants are forced by using polytunnels, flat plastic, or fleece covers to protect them from the cold. Additionally, many vegetables are pre-cultivated as seedlings in the greenhouse during periods, where outdoor growing is unfavorable and then transferred as transplants into the field (e.g. lettuce, Brassica), giving them a head start versus weeds and seeded vegetables.

BOX 1

Projections of temperature and precipitation over Europe and Germany.

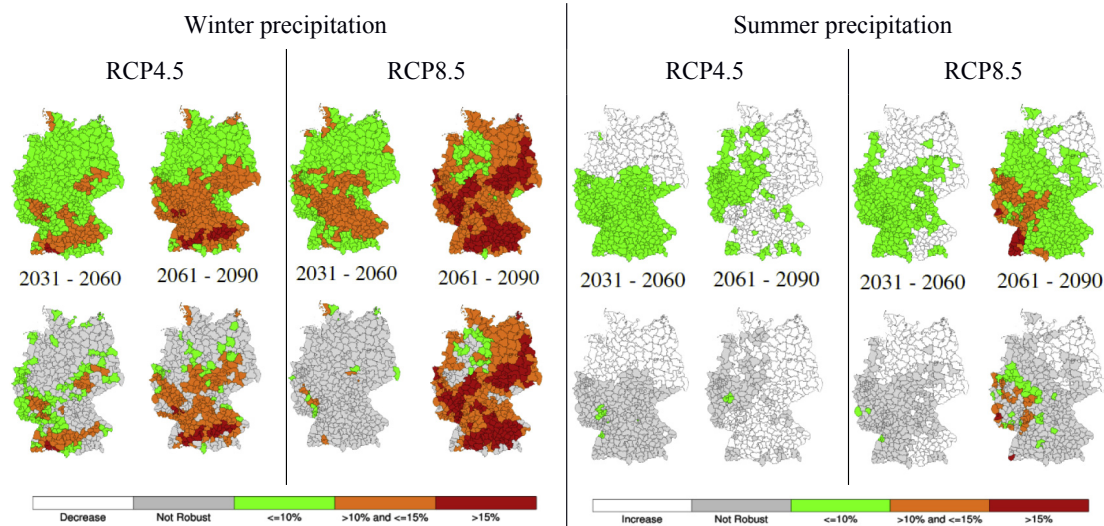
Temperature. Regional climate models (RCMs) are still related to a number of uncertainties and sometimes give contradictory results (Jacob et al., 2014). Recently the EURO – CORDEX project aimed at downscaling the horizontal resolution of climate models and evaluated several RCMs from different regions, in order to improve the reliance of climate change simulations across Europe. The term robustness describes the variability among different climate models, hence, when they are in accordance, results are robust (Pfeifer et al., 2014). According to Jacob et al. (2008), winters warm more than summers and, autumns more than springs. From 1961 to 2005, the thermal growing season, which is the annual period with mean air temperature above 5 °C, extended by 35 days (Chmielewski, 2007). Future trends describe a further increase of 26 days (RCP4.5), and of 58 days (RCP8.5) by the year 2071–2100 in relation to 1971–2000 (Jacob et al., 2014).

BOX 1a. Projected changes of annual mean temperature (K) for 2071–2100 compared to 1971–2000, for RCP8.5 and RCP 4.5 (taken from Jacob et al., 2014; with permission).



Precipitation. Total annual precipitation over central Europe increases by 1–13% (RCP4.5) and by 4–19% (RCP8.5) until the end of the century with respect to 1971–2000 (Jacob et al., 2014). Regional and seasonal patterns will show differences and there are large variations among models. Since summer precipitations are generally projected to decrease, any increase in annual precipitation might result from more rain during other seasons (Jacob et al., 2008). Winter precipitation will express mainly as rainfall rather than snowfall (Jacob et al., 2008).

BOX 1b. Increase of winter precipitation (%) and decrease of summer precipitation (%) compared to the reference period 1971–2000. Color coded: median of 10 RCM simulations from the EURO-CORDEX simulations. For the top panels, no test was applied to the data. In the lower panels, regions that failed at least one of the two robustness tests are grayed out (taken from Pfeifer et al., 2014; with permission).



EURO-CORDEX = European branch of the international Coordinated Downscaling Experiment (CORDEX); RCP = Representative Concentration Pathway.

The forecast of an extending cultivation season is likely to increase annual yields due to additional planting sets, since vegetables are often produced in a system of repeated planting after 7–14 days, allowing a continuously fresh market supply. Warmer

temperatures, with a longer ripening season in autumn might also facilitate the introduction of exotic crop species exclusively grown in Southern Europe e.g. melons (Fink et al., 2009). This might lower their carbon footprint as they may be produced locally, reducing

the share of imports from afar (Blanke and Burdick, 2005).

With increasing spring temperatures soils will warm earlier which combined with increased precipitation would largely benefit germination of sowed vegetables (e.g. carrot, onion, field cucumber, sweet corn) as well as, to a lesser extent, the growing and rooting conditions for transplanted crops (Peet and Wolfe, 2000). Long lasting precipitation might, however, retard some production steps, e.g. sowing or harvest, by making soils muddy and inaccessible for agricultural machines, resulting in unmarketable harvests or a shift towards periods with low market prices. Extreme rainfall caused lower yields of garlic, cucumbers and carrots in simulated future scenarios (Potop et al., 2011). Hence, higher temperature and precipitation will be beneficial only in the absence of extreme weather conditions that may hinder production steps, seed germination, and cause damage to delicate seedlings. As to that, Lattauschke (2015a) observed in onion that the initially rainy weather with good germination conditions was followed by lasting periods of drought, causing soil crusting, and in turn preventing roots to penetrate and seedlings to emerge. Late-frost further aggravated the outcome and delayed field emergence by up to 20 days with a resulting yield loss. Interestingly, simulations have shown that climate change may cause an advance of the date of last spring-frost, yet the benefits of a reduced frost-risk derive primarily from the delay in the date of first frost in autumn (Potop et al., 2014).

Milder winters will be characterized by higher temperatures that shorten the frost-period, with precipitation expressing mainly as rainfall rather than snowfall (Jacob et al., 2008). Vegetable production during these months is concentrated in greenhouses, but in some regions with mild winters, cauliflower, Brussels sprouts, lamb's lettuce, endive, spinach and some other cold season vegetables can be grown in the field. The high vulnerability to frost damage during this season often results in crop failure, but climate change might make over winter vegetable production more attractive and less risky for vegetable growers of different regions, thereby enabling a year round market supply (Fink et al., 2009; Flaig, 2013).

In conclusion, higher spring temperatures and the delay of the cold season in autumn as well as more rainfall may result in earlier and better conditions for seeded vegetables, and an extension of the period with favorable growing conditions, thereby providing a longer market supply at both ends of the season, more regional food and making winter cultivation financially rewarding. Extreme weather events might, however, cause serious damage and substantially reduce those potential benefits. While the overall risk of frost during the season decreases, risk of late-frost in spring remains high and increased rainfall might prohibit or retard some production steps and interfere with the planning process.

5.2. Insufficient winter chill and vernalization

Perennial vegetables such as asparagus and rhubarb require a stage of winter dormancy in which plant metabolism is reduced to a minimum and which is overcome through the accumulation of cold temperatures of 0 °C–7 °C. Assuming that warmer winters adversely affect chilling, Nie et al. (2016) studied temperature requirements for the induction and breaking of dormancy in asparagus cv. 'Applo'. Dormancy was overcome after 30 days at 2 °C and after 45 days at 5 °C, with reductions in bud break and spear production under shorter chilling duration. With 27,000 ha, white asparagus is the major field vegetable grown in Germany, and chilling for both asparagus and rhubarb might not be secured in every winter due to shortage or duration of cold winter temperatures resulting in substantial financial losses for producers.

Vernalization is a similar accumulation of cool units by vegetables during the growing season. Flower induction is impaired at temperatures between 12 °C and 16 °C in many species of e.g.

Brassicaceae, Alliaceae, Asteraceae. Vernalization can be desired or undesired in vegetables. In crops, where vernalization is undesirable such as lettuce, spinach or cabbage, flower induction (bolting) spoils the product for consumption with a strong, bitter taste and tough texture, hence an unmarketable waste product. Contrarily, e.g. in cauliflower, vernalization at 7–10 °C is desired and obligatory, and new cultivars are bred to secure flowering even at high temperatures (Laber and Lattauschke, 2014). Nevertheless, the process of flowering might be delayed, and the vegetative growth stage extended due to high temperatures, which is known as heat delay (Gruda and Tanny, 2014). Wurr et al. (1996), showed that curd formation in cauliflower could be delayed by up to 49 days when mean temperature was only 2.9 °C above ambient. This is often observed in summer during periods of heat, causing a batch of plants to be delayed and finish in parallel to later planting sets, flooding the market after a period of low market supply, with product prices falling drastically. In Germany, this is known as "the white weeks" for cauliflower; such irregularities may be more pronounced under future climate change. In spring, the covering material may have to be removed earlier in order to prevent adverse effects of overheating, which may even result in the absence of head induction (Peet and Wolfe, 2000).

In the context of climate change, some early vegetables may benefit from rising spring temperatures, a lower rate of vernalization, and a lower risk of crop failures, especially under protective covers. Contrarily, some field crops that require a period of vernalization in order to produce their harvest organ might experience increasing difficulties, especially in summer when temperatures are excessively high, causing more market irregularities.

5.3. Greenhouse production in warmer winters

In the greenhouse, climate is controlled by a wide range of technical tools that allow temperature to be manipulated to a certain degree, so that plant growth, yield, and quality are less dependent on outside temperatures compared to the open field. Winter greenhouse production in northern latitudes is marked by high heating efforts that depend on the cultivated species. For cold season crops, e.g. lettuce, greenhouses are generally operated at 12 °C, and this type is referred to as cold house production. The hothouse is characterized by heating efforts to beyond 18 °C and is applicable to warm season crops, e.g. tomato. Hoffmann and Rath (2009) simulated the future energy use of a 1 ha Venlo type greenhouse under the climate scenarios A2 and B1. Cold houses showed greater decreases of energy consumption in the south-eastern area of Germany due to high latitudes compared to northern or north-western regions in both scenarios. Trends for hothouse production were similar but showed greater decreases in the east than in the west for A2. A warming of the winter climate will reduce production cost as a result of lower heating requirements in the cold winter season (Olesen and Bindi, 2002). However, higher temperatures also increase crop transpiration which often results in excessively high humidity in winter. Energy savings by reduced heating requirement might be reversed by increasing energy input for dehumidification or increased energy losses through ventilation (Fink et al., 2009).

6. Impacts on product quality

Climate change affects the product quality of field-grown vegetables, and to a lesser extent, that of greenhouse-grown vegetables. Changing the climate condition in the greenhouse affects the physiological processes that lead to differences in appearance of vegetable products, and influence sensory ingredients such as sugars, acids, and flavor substances, as well as vitamins and

Table 5
Effect of high CO₂ on vegetable quality.

Quality parameter	Effect	Observed in	CO ₂ concentration	Reference
Sugars	↑	red leaf lettuce Chinese cabbage	1000 ppm 800–1000 ppm	Becker and Kläring (2016) Jin et al. (2009)
Macronutrients (N, P, K, S, Mg)	↓	lettuce, spinach	700 ppm	Giri et al. (2016)
Micronutrients (Cu, Zn)	↓	lettuce, spinach	700 ppm	Giri et al. (2016)
Vitamin C	↑	leaf and stem lettuce, celery, Chinese cabbage,	800–1000 ppm	Jin et al. (2009)
Antioxidant capacity (phenols, flavonoid)	↑	red/green leaf lettuce, spinach	700–1000 ppm	Giri et al. (2016); Becker and Kläring (2016)
Nitrate content	↓	leaf and stem lettuce, celery, Chinese cabbage,	800–1000 ppm	Jin et al. (2009)

Table 6
High temperature effect on vegetable phenology and yield.

Reduced crop duration in:	Temperature	Yield	Reference
Common bean	27/22 °C	↓	Siddique and Goodwin (1980)
Pea	24 °C	↓	Wien (1997); Lattauschke (2015b)
Lettuce	21 °C	↓	Wheeler et al. (1993)
Onion	19 °C	↓	Daymond et al. (1997); Coolong and Randle (2003)
Increased crop duration in:	Temperature		Reference
Cauliflower	Ambient + 4 °C		Wurr et al. (1996)
Broccoli cv. Ironman	12.8–20.9 °C		Lindemann-Zutz et al. (2016)

secondary plant compounds (Gruda, 2005, 2009). Wang and Frei (2011) have shown that slightly stressed plants could produce higher quality products in terms of inner ingredients, and that the timing of stress events played an important role with higher effects at late stages near harvest. However, excessive environmental stresses often adversely affect vegetable quality in a way that the product becomes unmarketable, thereby increasing wastage during the production cycle.

6.1. Product quality under elevated CO₂

Although increasing CO₂ concentrations promote plant growth and yields of vegetable crops, they may alter their nutritional quality (Table 5). Becker and Kläring (2016) showed that sugars, flavonoids and caffeic acid derivatives increased in red leaf lettuce grown at 1000 ppm CO₂. Similarly, Jin et al. (2009) showed that leaf and stem lettuce, celery, and Chinese cabbage grown at 800–1000 ppm CO₂ contained more vitamin C hence higher antioxidant capacity, while nitrate content was reduced except in stem lettuce. Soluble sugars were increased only in Chinese cabbage. At elevated CO₂ (700 ppm; control: 400 ppm), Giri et al. (2016) reported a rise in total phenolic content and antioxidant capacity, by 63% and 49% respectively, in lettuce and spinach. However, the authors observed a significant reduction of several macro- and micronutrients in the edible parts of both, lettuce and spinach. In tomato, higher amounts of sugar and vitamin C were reported but the fruits ripened slower with reductions in citric and malic acid (Moretti et al., 2010). The few studies mostly with leafy vegetables on enriched CO₂ effects on product quality indicate a possible enrichment in sugars, ascorbic acid (vitamin C), phenols, flavonoids, and antioxidant capacity, while macro- and micronutrients decreased.

6.2. Temperature effect on phenology and product quality

Temperature steers chemical and differentiation processes

within the plant thereby determining growth speed, development rate, and the growth period of horticultural crops. White asparagus, for instance, is traditionally cultivated in dams due to the earlier warming in spring, and hence earlier growth. Double-sided plastic mulch, where the white side has a delaying, and the black side has an advancing effect, are used to force earlier spear growth. The black side is often combined under plastic tunnels for an even earlier harvest. However, an excessive heating of the dam and warm air around the shoots are among the factors responsible for quicker head opening and the purple discoloration sometimes observed on white asparagus (Laber and Lattauschke, 2014). The share of undesirable fibers in the spears might as well increase (Peet and Wolfe, 2000). The occurrence of open heads, purple discoloration and fibers in asparagus reduces quality, price and consumer acceptance and might be enhanced by climate change. Producers might have to turn over the plastic mulch from black to white earlier in order to prevent excessive heating and deterioration of product quality.

During their life cycle, vegetables undergo various developmental stages also known as phenological stages, which are highly temperature dependent. In determinate crops, e.g. peas and beans, flowering is induced only after exposure to a defined minimum number of day-degrees above a certain base temperature, known as the temperature sum (Peet and Wolfe, 2000). After flowering, determinate species cease growth, produce fruits and after harvest their life cycle ends. Global warming might speed up development of such vegetables and thereby shorten crop duration and the period for photoassimilation, which on the one hand may be desirable due to earlier crop maturation and the arising possibility to plant more sets, but on the other hand could result in reduced yields and product quality when thresholds are exceeded (Table 6).

In bush bean, flower expression is accelerated at temperatures between 25 and 30 °C, but only in day neutral cultivars i.e. independent of photoperiod, which predominate in Germany (Laber and Lattauschke, 2014). Siddique and Goodwin (1980), showed in a glasshouse study that common bean (*Phaseolus vulgaris* L.) grown

at temperatures above 27/22 °C (day/night) during seed development matured early and produced small seeds compared to beans grown at 21/16 °C. Similarly, high temperatures accelerated development of pea plants, thereby reducing their crop duration, biomass production and yield, e.g. at 24 °C compared to 16 °C mean in CE chambers (Wien, 1997). Even shorter periods of extreme heat were found to saturate temperature sums prematurely with earlier harvests of 2–5 days and quality losses in terms of reduced seed size in late pea cultivars (Lattauschke, 2015b). In their studies on head lettuce under 16.3 °C–21.1 °C, Wheeler et al. (1993) found growth was favored by the larger temperature in the early stages, but development was accelerated, which resulted in a 17% yield loss. Temperatures above 17–28/3–12 °C (day/night) increased the portion of loose and puffy heads, tipburn and leaf chlorosis with an accumulation of bitter compounds (Wien, 1997). In onions, yields nearly doubled at 12 °C as compared to 19 °C, due to the reduced period of bulb growth (12 °C: 117 days; 19 °C: 55 days) (Daymond et al., 1997). Coolong and Randle (2003) reported lowest fresh weight at 15.6 °C and 32.2 °C as compared to the onions grown at 22.1 and 26.7 °C, with their organic sulfur contents as a flavor precursor increasing linearly with rising temperatures.

By contrast, indeterminate crops appear less vulnerable to increases in the speed of phenological development, because flowering is induced depending on photoperiod (e.g. climbing and straggling beans) or independent of both, temperature sum and photoperiod (e.g. tomato) (Wien, 1997). Indeterminate crops can often be harvested while new fruits are produced since ripening and flower expression occur simultaneously, but this does not apply for all species. Carrot and beetroot for instance appear to be indeterminate and are expected to benefit from warmer temperatures, as growth is affected positively, while developmental stages remain unaffected; in theory, this results in higher yield (Peet and Wolfe, 2000). However, Rosenfeld et al. (1998) found higher root

weights when the carrots were grown at 12 °C and 18 °C compared to 21 °C; sugar contents declined with rising temperatures, but taste improved. In carrot, both the amount of carotene, responsible for orange root coloration, peaked between 15.5 and 21.1 °C (Saha et al., 2016) and monoterpenes as well as sesquiterpenes, both components of essential oils, accumulated under high temperatures (Ibrahim et al., 2006).

Even though vegetables are generally classified as either determinate or indeterminate, there is variability among cultivars within species. In broccoli, cvs. 'Cruiser', 'Skiff', 'Fiesta' and 'Lord', a linear correlation between increasing mean temperatures and increasing developmental and growth rates was observed (Kalużewicz et al., 2009; Mølmann et al., 2015). On the contrary, Lindemann-Zutz et al. (2016) found higher growth temperatures to increase the length of the lifecycle in broccoli cv. 'Ironman', because developmental rates slowed down between 12.8 and 20.9 °C and flowering was delayed. The speed of growth in broccoli is involved in the incidence of hollow-stem, a disorder possibly related to boron deficiency (Boersma et al., 2009) that could occur more often when growth rates increase, e.g. by applying high N doses, with negative effects on product quality (Gruda and Heine, 2002). Broccoli heads in cool locations (12 °C) were sweeter and more uniform in bud size, but with a staler flavor and a higher color hue compared to 18 °C (Mølmann et al., 2015). In the warmer location, broccoli contained more flavonols in florets with altered glucosinolates composition.

In conclusion, determinate vegetables might suffer from faster development due to climate change, possibly resulting in reduced yield and product quality. According to Keatinge et al. (2012), this could lead to medium-duration cultivars becoming early cultivars, late cultivars becoming medium-duration, and early cultivars becoming increasingly vulnerable. In theory indeterminate crops are expected to benefit from climate change, but further evidence

Table 7
High temperature effect on vegetable product quality.

	Effect	Observed in	Reference
External quality			
Tip fill (cob)	↓	sweet corn	Wien (1997)
Tipburn	↑	lettuce, broccoli, chinese cabbage	Saure (1998); Gruda and Tanny (2014)
Seed and fruit size	↓	bean, pea, tomato	Siddique and Goodwin (1980); Lattauschke (2015b); Gruda (2005)
Fibres	↑	bean, asparagus	Peet and Wolfe (2000)
Bracting	↑	cauliflower, broccoli	Wiebe, 1972
Flower bud size	↑	broccoli	Kalużewicz et al. (2009)
Hollow stem	↑	broccoli	Boersma et al. (2009)
Loose heads	↑	broccoli, lettuce	Kalużewicz et al. (2009); Wien (1997)
Bulb splitting	↑	onion	Peet and Wolfe (2000)
Fruit coloration	↓	tomato	Gruda and Tanny (2014)
Fruit cracking	↑	tomato, pepper	Gruda (2005), Rosales et al. (2010); Gruda and Tanny (2014)
Sunburn	↑	pea, tomato, pepper	Lattauschke (2015b); Rosales et al. (2010); Gruda and Tanny (2014)
Blossom-end rot	↑	tomato, pepper	Rosales et al. (2010); Gruda and Tanny (2014)
Green shoulders	↑	tomato	Gruda and Tanny (2014)
Internal quality			
Sugar content	↓	Pea, tomato, cabbage, melon, sweet corn	Rosales et al. (2010); Gruda and Tanny (2014); Wien (1997)
Starch	↓	Sweet corn	Wang and Frei (2011)
Macronutrients (K, Mg, Ca)	↓	Tomato	Rosales et al. (2010)
Micronutrients (Fe, Zn, Mn, Cu)	=	Tomato	Rosales et al. (2010)
Ascorbic acid (Vitamin C)	↑	Tomato, lettuce	Rosales et al. (2010)
	↓	Tomato	Wang and Frei (2011)
	=	broccoli	Mølmann et al. (2015)
Tocopherol (Vitamin E)	↑	Lettuce	Wang and Frei (2011)
Lycopene	↓	Tomato	Gruda (2005); Rosales et al. (2010)
Carotene	↓	Carrot, tomato, lettuce	Ibrahim et al. (2006); Rosales et al. (2010); Wang and Frei (2011)
Antioxidants (anthocyanin, flavonols, phenols, glycosinolates)	↑	Tomato, Brassica species e.g. broccoli	Rosales et al. (2010); Gruda (2005); Mølmann et al. (2015)
Organic S (flavor)	↑	Onion	Coolong and Randle (2003)
Terpenes	↑	Carrot	Ibrahim et al. (2006)
Bitter compounds	↑	Lettuce	Wien (1997)

for this claim has to be provided since experimental results have shown a different trend. Furthermore, differences among cultivars of the same plant species indicate that further investigations should be made.

6.3. Summer heat waves reduce fruit-set and product quality

The probability of heat waves has doubled in Europe over the last decades, with likely further increases in their future frequency and duration (IPCC, 2013). Heat spells are characterized by temperatures exceeding 30 °C and intense solar radiation at an unfavorable vapor pressure deficit (VPD). In 2015, temperatures in Germany peaked at 40.3 °C in Kitzingen. In horticulture, such conditions can have serious implications on plant growth, health, yield, and product quality (Table 7), due to damages in cellular membranes, proteins, nucleic acids, and the adverse effects on pigment synthesis and degradation (Gruda and Tanny, 2014). This review only focuses on heat stress situations, hence drought and decreasing precipitations have been excluded since in Western Europe vegetable crops are subject to intense irrigation. Controlled drought stress may however increase product quality with higher carotenoid and ascorbate contents in tomato, pepper, and carrot, as well as more sugars in tomato and cucumber (Wang and Frei, 2011).

6.3.1. Flowering and fruit set

High temperatures during flowering can have detrimental effects on the morphology and the functioning of reproductive organs. In sweet corn, anomalies in the flowering organs (tassel ear) can result from periods of heat, with adverse effects on ovule fertilization and hence insufficient tip-fill (Wien, 1997), causing reduced grain development and lower husk cover. This reduces the market value, and with empty pockets in the cob, increases production waste. High temperatures during harvest also speeds up sugar degradation, thus narrowing the harvest window for optimum yields with high sugar content and delicate texture (Peet and Wolfe, 2000). Fruit set, a prerequisite for yield in fruiting vegetables, relies on pollen release and germination (Sato et al., 2000), which can both be impaired by exposure to heat (Li et al., 2012). In heat-sensitive common bean cultivars (*Phaseolus vulgaris* L.), temperatures of 32/27 °C (day/night), caused abnormal pollen and anther development, poor ovule fertilization and increased flower abscission with a resulting low yield (Porch and Jahn, 2001). Abdelmageed and Gruda (2007) reported impeded pollen production and release, with a reduced fruit set at 37/27 °C (day/night) in tomato. The same authors showed that high night temperatures (37/27 °C compared to 37/22 °C day/night) reduced fruit set, but only in sensitive varieties, with increased occurrence of flower abortion, fruit abscission, parthenocarpic and undeveloped fruit in all cultivars (Abdelmageed and Gruda, 2009b).

Climate change related heat waves might, hence, adversely affect anther and pollen development, release, and germination on the stigma, poor ovule fertilization, and reduced fruit set due to flower and fruit abscission. All of these reduce yield and cause an increase in parthenocarpic fruit e.g. tomato as well as underdeveloped fruits e.g. tip-fill in sweet corn, and thereby raise production waste and economic losses for producers.

6.3.2. Open field production

During heat waves, open field vegetables are directly exposed to excessively high temperatures and radiation. Tipburn in head lettuce is a common disorder under these circumstances, and is related to high transpiration and unequal calcium allocation (Peet and Wolfe, 2000). Excessive radiation may damage lettuce and cabbage, with leaves becoming papery and resulting in sunburn (Moretti et al., 2010). But these circumstances might as well

increase, ascorbate (Vitamin C), carotene, and tocopherol (Vitamin E) content in lettuce (Wang and Frei, 2011). In broccoli, heat can cause disorders and malformations such as uneven heads with over-sized flower buds even at temperatures of only 25 °C (Kałużewicz et al., 2009), sometimes with yellow discolorations. During this head formation stage, heat may cause bracting in sensitive cultivars (Wiebe, 1972), whereas temperatures above 25 °C at harvest induced premature ripening with loose, puffy heads (Kałużewicz et al., 2009). Modifications of sensory and phytochemical composition of the broccoli florets were described by Mölmann et al. (2015) (Table 7). In asparagus, periods of combined heat and drought stress may result in the wilting of shoot tips, as a consequence of a disturbed calcium metabolism (Laber and Lattauschke, 2014). Calcium deficit in asparagus may cause a continuous development of new shoots, which subsequently wilt, thereby reducing photo-assimilate and nutrient translocation to the rhizome as the storage organ, which is thereby stalled in growth (Feller and Jaworski, 2016). The hot spell in Germany in 2015, with high radiation and temperatures of 37 °C induced wilting of onion foliage within a few days (Lattauschke, 2015a), causing premature ripening, despite adequate irrigation, and reduced yields, however, with no change in product quality. High temperatures might also increase bulb splitting (Peet and Wolfe, 2000). In the same hot year, Lattauschke (2015b) observed reduced fruit set and seed size in pea and many pods were affected by sunscald.

Heat waves may decrease head appearance in field-grown lettuce and broccoli, tip burn in lettuce and premature senescence of newly developed asparagus shoots due to unequal calcium allocation as well as sunburn on leaves e.g. of lettuce and cabbage and fruit such as pea pods, tomato, and pepper. Simulations showed that heat waves reduced vegetable yields, particularly of onion, pea, cabbage, cauliflower, and Savoy cabbage (Potop et al., 2011). Research should therefore be conducted on innovative methods to protect vegetable plants from heat waves, even in large scale field cultivation.

6.3.3. Greenhouse production

In greenhouses, heat waves can cause undesirably high temperatures, especially in older constructions with insufficient ventilation capacity, causing difficulties in climate management (Fink et al., 2009).

Tomato is the main agricultural product grown in northern latitudes greenhouses and the most consumed vegetable in Germany. In tomato and pepper, sun scald, cracked fruits, and blossom-end rot (BER) are common, while uneven ripening and green shoulders were reported exclusively in tomatoes (Gruda, 2005; Rosales et al., 2010). Heat stress can decrease fruit weight in tomato (Abdelmageed and Gruda, 2009a, 2009b). But not only fruit appearance is adversely affected, also ingredients such as acid, sugar, and lycopene content can cause adverse effects on taste and flavor. Lycopene is the health promoting dietary compound in tomato and is responsible for fruit color. Lycopene synthesis is inhibited above 32 °C (Gruda and Tanny, 2014), which has been demonstrated by Rosales et al. (2010). High temperature, irradiance, and low vapor pressure deficit (VPD) reduced lycopene content while β -carotene remained either unchanged in the hotter parral type greenhouse or increased in their multi-span greenhouse. Heat promotes the oxidation of lycopene into β -carotene, which explains the rise of the latter in the multi-span greenhouse; the restricted climate control in the low-cost parral greenhouse resulted in such high temperature, under which β -carotene is degraded, while the simultaneous formation and degradation of β -carotene explained the overall unchanged amounts (Rosales et al., 2010). Increased contents of phytonutrients, such as phenols

(rutein, caffeic acid), flavonoids, ascorbic acid (vitamin C), and anthocyanin, were among the positive aspects of a high temperature, irradiation, and vapor pressure deficit (VPD), resulting in a higher antioxidant capacity (Table 7). However, ascorbate content in tomato might as well be decreased due to heat stress as stated by Wang and Frei (2011), and Gruda and Tanny (2014) reported a suppressed sugar accumulation in cherry tomatoes, melon, and watermelon. Similarly, in Brassicas (*Brassica oleracea* L.), total leaf glucosinolates, glucoraphanin, but also the incidence of tipburn in e.g. Chinese cabbage, may be increased at high temperatures (Gruda, 2005; Gruda and Tanny, 2014).

6.4. Greenhouse climate during milder winters affect product quality

With climate change and the related rise in winter temperatures, growers might have to face increased problems with high relative humidity (RH) due to enhanced transpiration.

The product quality of all-year round produced tomato, cucumber or lettuce might suffer from high RH in winter, if climate is not properly managed. The interaction of RH with transpiration, calcium (Ca) uptake and allocation within the plant can result in Ca related physiological disorders such as tipburn in lettuce, cabbage, Chinese cabbage, and fennel; BER and gold specs in tomato and pepper; blackheart in celery (Hand, 1988; Olle and Bender, 2009). Contrarily, elevating RH to 100% at night, reduced tipburn in butterhead lettuce, due to less transpiration at high RH, which increases root pressure and allocates sufficient calcium towards low-transpiring organs such as fruits (Saure, 1998; Vanhassel et al., 2015).

Seedlings, pre-cultivated in greenhouses during the winter under high RH, may benefit from propagation, e.g. in the grafting process (Gruda and Tanny, 2014). Low VPDs of 0.2–1.0 kPa have no major effect on growth and development of greenhouse horticultural crops (Grange and Hand, 1987). However, further humidity

increases towards condensation and droplet formation on the leaves increase the risk of grey mold (*Botrytis cinerea*) and leaf mold (*Fulvia fulva*) in tomato, and downy mildew (*Bremia lactucae*) in lettuce (Hand, 1988).

In conclusion, higher RH during the day might cause increased problems with Ca related disorders while an increase at night seems to be beneficial in preventing these disorders. Higher RH could be beneficial in transplant production. However, in both cases, higher RH might result in more fungal diseases. Greenhouse climate management is of utmost importance and growers should therefore invest in advanced technologies for a better control to maintain optimum conditions.

6.5. Impacts on post-harvest quality

Environmental growing conditions and stress factors, do not only affect the quality of fresh vegetables at harvest, but strongly influence storage and shelf-life (Toivonen and Hodges, 2011; Farneti et al., 2013). Lettuce affected by tipburn at harvest is more susceptible to soft rot during storage, whereas leaves of lettuce and cabbage damaged by sun scald are more susceptible to decay (Moretti et al., 2010). Reductions in the surface to volume ratio of fruit vegetables, e.g. when tomato size shrinks due to heat stress (Gruda, 2005), naturally enhances moisture loss in storage (Toivonen and Hodges, 2011). Heat stress may also increase electrolyte leakage during storage (Moretti et al., 2010). When grown under low water supply, Conesa et al. (2014) showed that shelf life of tomato might be extended and post-harvest weight loss reduced. By contrast, pre-harvest drought stress in carrot can result in faster water loss at post-harvest stages and may make some fruits more susceptible to chilling injury during cooling (Toivonen and Hodges, 2011). After transpiration, the other important post-harvest factor to control is respiration, which is why fruits and vegetables are usually refrigerated (Moretti et al., 2010). With climate change, vegetables are expected to be harvested at greater produce temperatures, thereby

Table 8
Adaptation strategies to mitigate adverse impacts of climate change.

Variable	Problem	Adaptation	Reference.
Extreme precipitation	Water logging on field Soil erosion	Installation and maintenance of field drainage	a)
		Increasing soil cover and organic matter by reduced tillage practice	b)
Summer drought	Reduced water availability and increasing irrigation demand	Mulching minimizes soil evaporation losses	b), c)
		Drip irrigation combined with tensiometers increases irrigation efficiency	d), e)
		Deep wells, bank filtrate, rainwater harvesting, aquifer recharge ponds, retention dams secure and store water resources	a), f)
Heat waves	Heat stress leads to yield and quality losses	Reduce solar radiation by shading devices	b), g)
		Increase heat and drought tolerance through grafting and breeding	h), c)
Pest and disease	Excessive heat accumulation in greenhouses	Modernization of greenhouse constructions with improved ventilation and advanced climate control	i)
		Increased use of pesticides with respect to limit values and a broad range of active agents to avoid host resistance	i), j)
		Weed suppressing soil cover and insect screens	k)
		Breeding for pest resistance	l), m)

^a Dietrich et al. (2015).

^b Flaig (2013).

^c De la Peña and Hughes (2007).

^d Schneider (2016).

^e Buttaro et al. (2015).

^f Moriondo et al. (2010).

^g Shahak (2008).

^h Abdelmageed and Gruda (2009a).

ⁱ Fink et al. (2009).

^j Hullé et al. (2010).

^k Jamieson et al. (2012).

^l Mattos et al. (2014).

^m Van de Perre et al. (2014).

increasing the amount of energy consumption for cooling. Despite ozone-induced leaf chlorosis, necrosis, and altered composition of starch and sugars in root, tuber, and fruit vegetables, the shelf-life of broccoli and seedless cucumber can be improved (Moretti et al., 2010). For other species improved cultivars with an extended shelf life should be subject of future research.

7. Adaptation is the key to sustainable horticulture

After identifying the potential adverse effects of climate change on product quality that might challenge the sustainability in vegetable production, possible adaptation strategies are discussed in order to maintain the quality of fresh vegetables and reduce the wastage potential in the future. Adapting to climate change includes securing water and nutrient supply while reducing the damages caused by extreme weather events (heat waves, heavy rain) as well as adapting the gene-pool of cultivars to the new growing conditions (Table 8). Implementing adaptation strategies becomes increasingly important in order to benefit from the positive aspects such as high CO₂ extended growth period for summer crops and cultivation of winter crops.

7.1. Integrated water management

The shift in precipitation pattern, as well as increasing weather variability and extreme weather events such as heavy rain, heat waves, or drought, make water management a key factor in combating the adverse impacts of climate change. Total annual precipitation is projected to increase until the end of the century (BOX 1). However, the climatic water balance, which is the difference between precipitation and evapo-transpiration of the crop canopy and the soil, is projected to become increasingly negative during the growing season, where water is required in large quantities (Berthold, 2009).

In times of increased rainfall, as projected for spring and autumn, water logging on heavy soils with poor drainage may result in anaerobic soil conditions, reducing plant growth and disabling agricultural machinery to work on the vegetable field. Drainage systems are common in Germany, and remove excess water, but in many cases they are attrited and need to be refurbished (Dietrich et al., 2015). The drained water should be stored for usage in times of scarcity. If the latter problems are avoided, earlier planting in spring, and later planting in autumn become increasingly important in order to profit from the increased rainfall during this time, enabling crop production with less irrigation.

Storms and hail can mechanically damage leaves and fruits of horticultural crops, with hail nets being the common countermeasure (Solomakhin and Blanke, 2010; Flaig, 2013). Heavy rainfall is also on the increase in Germany (Blanke and Kunz, 2010) and can cause soil erosion particularly in winter and spring, and thus a loss of fertile land. This can be avoided by reduced tillage practices, integration of cover- and catch crops to reduce fallowness, as well as improving water holding capacity in soils by raising the content of organic matter (Ernst, 2012). Reduced tillage in vegetable production systems may increase soil organic matter, but needs to become more profitable for producers while fulfilling the requirements of both, markets, and ecological issues.

Even though we excluded drought stress, we will emphasize securing irrigation water resources in order to ensure plants are spared from periods of scarce water supply. The extended growing season as well as the negative climatic water balance during the growing season will demand higher amounts of fertilizer and a compensation of the water deficit by higher amounts of irrigation (Moriondo et al., 2010; Flaig, 2013). The future increase in water deficit has been simulated for the Hessian Reed (Berthold, 2009).

Water scarcity in summer ultimately increases the competition between stakeholders e.g. industry, drinking water, and agriculture, which already had negative effects on vegetable growers in Central Valley in California (Ebel, 2015). In order to secure sufficient irrigation in agriculture, integrated ground- and surface water management is of utmost importance. When using blue waters, Schneider (2016) suggested using river or lake bank filtrate as a sustainable option rather than extracting water directly, which may result in dry pumping and requires higher operation costs for pumps. There is the possibility of increasing storage capacity of surface waters e.g. by building water retention reservoirs and dams, whereas groundwater aquifers can be refilled e.g. by recharge ponds (Moriondo et al., 2010). Aquifer recharge seems to be a suitable method, because water surplus at times of high precipitation can be stored and used at later stages e.g. during drought. Furthermore, harvesting rainwater into water reservoirs at times of intense rainfall might become essential for vegetable growers in dry regions (Moriondo et al., 2010).

Besides securing sufficient water amounts, it becomes increasingly important to improve the use efficiency of this resource by avoiding unnecessary water losses. Direct radiation on uncovered soil results in soil evaporation, hence water loss, which can be reduced by soil covering, e.g. organic, plastic or fleece mulch, integration of catch crops, and reduced tillage (De la Peña and Hughes, 2007; Flaig, 2013). A good practice is for instance the combined application of mulch foil with a layer of straw (De la Peña and Hughes, 2007), but this technique is crop dependent. Catch crops should be chosen with respect to a low water requirement in order to minimize competition (Flaig, 2013). Water losses by driftage and evaporation during sprinkling cause an unequal water distribution (Teichert, 2009), and can be avoided by more efficient irrigation techniques such as stationary and mobile drip irrigation, or mobile sprinklers (Schneider, 2016). Drip irrigation has the advantage of leaves remaining dry, as water is directly introduced to the root system. In the future, it might have to replace the commonly used sprinkler systems, despite the increased work load and higher cost (Teichert, 2009). Buttaro et al. (2015), showed that greenhouse tomatoes and cucumbers, under Mediterranean conditions, grown with a combination of drip irrigation, tensiometers, and soil covering used 35% and 46% less water respectively, and WUE was increased. However, the study showed that product quality and yield might be affected in terms of reduced fruit size.

In conclusion the use of lake or river bank filtrate is preferred over direct water extracting for irrigation. Water storage in water retention reservoirs can help overcome periods of high irrigation requirement and high competition between agriculture, industry, and population. A wider use of drip irrigation and mulches to reduce soil evapotranspiration, and sensors measuring the soil water content, are suitable tools to manage plant irrigation and conserve water.

7.2. Adaptation strategies to heat stress

Breeding heat and drought tolerant varieties with a better WUE (De la Peña and Hughes, 2007) as well as species specific traits such as secure vernalization for head formation, e.g. in cauliflower, is of crucial importance.

At the cultivation level, shading can protect vegetables and secure quality during heat waves in greenhouses (Gruda and Tanny, 2014). This method is so far uncommon for field vegetables, but future climate warming might require this in some instances (Ernst, 2012). There have been a number of studies on photo-selective shading nets in Mediterranean climate with excessive radiation. The increased portion of diffuse light and the changed light spectrum contributed to an increased yield of pepper, basil, and lettuce

(Shahak, 2008). However, there is no evidence of these advantages in temperate climates such as Germany, where light is a limiting growth factor and vegetables are shaded only for a few hours per day. Solomakhin and Blanke (2010) showed no positive effects when using colored hail-nets, with a low shading capacity, on apple orchards. Therefore, in Western European climates, systems of temporary shading in the field are required.

Transplant producers could contribute to heat stress tolerance by several techniques. Grafting sensitive cultivars on drought or heat tolerant root stocks may reduce the repercussions caused by heat stress (Abdelmageed and Gruda, 2009a; Altunlu and Gul, 2012). A heat shock of young plants at high temperatures and intense light may increase heat tolerance and can make photosystem II more resilient towards heat exposure (Allakhverdiev et al., 2008) by producing heat shock proteins. However, more research is needed in the field of heat shock pretreatment since results have shown no beneficial effects (Abdelmageed and Gruda, 2009a). Also, since permanent or temporary shading may become necessary even in field production, more research is required since it is rather uncommon in northern latitudes.

7.3. Adapting to increasing infestation of weeds, pests, and diseases

Altered temperature and precipitation rates are expected to cause weeds to emerge earlier while rising CO₂ will increase their growth rates and WUE (Mattos et al., 2014), ultimately increasing the competition between both, weeds and vegetables (Korres et al., 2016).

With the cold season becoming warmer, insects mortality will decrease possibly causing stronger infestations in the following season (Olesen and Bindi, 2002; Jamieson et al., 2012), while increasing atmospheric CO₂ might alter the feeding quality of the host (Dáder et al., 2016). Insect propagation is highly dependent on temperature, and warming would enable them to produce more generations per year, as Hullé et al. (2010) have shown for aphids. These aphids reacted to elevated temperature with an acceleration of phenology, hence earlier flights, and a disturbed synchrony between their emergence, and that of their natural enemies. A stronger proliferation of e.g. aphids and whiteflies could cause an increased spread of viruses in the future, since both are effective vectors (Keatinge et al., 2012). New species might also emerge, e.g. the South American leaf miner *Tuta absoluta* in tomato. Due to international trade, this devastating pest has been accidentally introduced in the Mediterranean recently and is able to overwinter in Western European greenhouses due to mild temperatures and short periods without plant cultivation (Van Damme et al., 2014). With increasing global temperatures, climate conditions shift towards more optimal conditions for such pests, and their importance might increase, even in the open field.

Heat and drought stress might furthermore shift the composition of leaf ingredients such as sugar, starch or secondary metabolites, increasing the attractiveness and palatability for pest insects (Gutbrodt et al., 2011; Jamieson et al., 2012), while increasing the susceptibility to fungal and bacterial invasion (Mattos et al., 2014; Hribar and Vidrih, 2015). *Alternaria* mold, might occur more frequently in cool regions e.g. Poland and less in warm regions e.g. Spain, ultimately altering mycotoxin content in fruits as Van de Perre et al. (2014) showed in tomato.

Additional applications of pesticide may be required and attention must be paid to limit residue values in fresh produce, with transgressions making the product unmarketable. Host-resistance should be avoided by developing a broad range of different active chemicals for plant protection. More sustainable alternatives might be the application of insect screens, weed suppressing mulch layers, and the breeding of new cultivars not only with heat and

drought tolerance, but also pest and disease resistance.

7.4. Adapting greenhouse vegetable production to climate change

Water, as a valuable resource, can be used more efficiently in protected vegetable production, which is considered less dependent on weather conditions than open field production because micro-climate can be manipulated. The use of polytunnels or greenhouses might therefore be a possible adaptation strategy to manage and conserve the resource water. Effective greenhouse production relies on environmental conditions. The site of the greenhouse determines framework conditions such as climate (irradiation, temperature, day length, rain etc.), edaphic (structure, chemical and biological soil properties, soil water and air content at different water tensions), and management (cultivation measures) (Gruda, 2009). These are the basic factors to consider in the decision process when constructing a greenhouse. The increased problems with high humidity in winter, as well as the increased incidence and duration of heat waves in summer, will require more effective climate control, which can only be achieved through innovative technologies. Shading, sufficient ventilation, and technical cooling might become indispensable in some locations during summer, and dehumidification units during winter (Fink et al., 2009). Hence, greenhouse locations should be carefully chosen with respect to future changes, and many older greenhouses need to be upgraded to higher technology standards.

Less greenhouse heating during the cold season as a result of global warming, might lead to lower energy costs in the future, but the source of energy such as fossil fuel are becoming increasingly expensive and will remain primary input factors, at least in the near future. Hence, recent research, e.g. the ZINEG low energy greenhouse project in Germany, focused on reducing the energy input and increasing the energy use efficiency in higher latitudes greenhouses by applying new covering materials, double and triple thermal screens, climate control strategies, and energy optimized cultivation programs (Tantau et al., 2015). It was calculated that lowering day and night temperature set points for tomato by 1 °C led to a reduction of 8% in annual heating energy consumption (Elings et al., 2005), but can adversely affect the leaf area development and light interception, resulting in lower production, extended development time and reduced product quality (Gruda and Tanny, 2015). Innovative greenhouse technologies could further contribute to decreasing energy consumption during the cold season, which is to be considered in the future. Alternatively, renewable energy sources such as waste energy, wood pellets, solar panels or geothermal energy are increasingly employed depending on the economic profitability of such an investment (Ruhm et al., 2009; Ernst, 2012). Despite the future reduction in heating demand, a shift towards renewable energy resources may be required, due to the ever increasing prices for fossil fuels.

In winter, low irradiance is an additional limiting factor in greenhouse production, adversely affecting plant performance (Gruda, 2005; Gruda and Tanny, 2014). Under such conditions, leaves become adapted to shade, which had negative effects on photosynthesis at elevated CO₂, when irradiation suddenly increased in spring (Tartachnyk and Blanke, 2007). This increase in photoinhibition, as well as yield and quality losses can be avoided by additional lighting, with a promising technology being LED lights, which are considered more energy efficient than the common high pressure sodium lamps (HPS) (Martineau et al., 2012; Gómez and Mitchell, 2013). The LED light spectrum can be controlled individually and their lifespan is often higher (Lin et al., 2013). In lettuce, they produced similar yields than HPS lamps, without quality reductions, while consuming less energy (Martineau et al., 2012). If winter production in greenhouses is to

expand in response to milder winters, LED lights may aid to overcome light limitations while making efficient use of electrical power.

8. Conclusions

Future climate change is associated with shifting environmental factors for growing vegetables such as increasing temperatures, atmospheric CO₂, atmospheric O₃, extreme weather events, and changes in the precipitation pattern. These climatic modifications will affect plant physiology, altering photosynthesis, and increasing respiration. High CO₂ generally increases vegetable yields and WUE due to reduced stomatal conductance, but may also result in growth depressions after long term exposure, as preliminarily shown in simulations and field studies with FACE (Fig. 1). Rising temperatures and radiation can stimulate growth and yield or reduce them, when thresholds are exceeded (photoinhibition). The interaction of radiation, temperature and CO₂ elevation can produce a synergistic effect in that rises in CO₂ improve heat stress tolerance, again depending on species. Further increases in O₃ produce toxic effects in vegetable plants and damages such as leaf chlorosis and necrosis with premature senescence and subsequent yield reductions. These constraints become less pronounced under rising atmospheric CO₂ levels. However, physiological responses of different vegetable species under climate change scenarios are still under-researched and should be studied in more detail, by simulation, but also by developing new methods of combined CO₂ and temperature elevation as well as O₃ enrichment in the field.

Increasing temperatures will extend the growing season in spring and autumn with higher annual yields and a longer market supply. Exploiting this additional time becomes increasingly

important, particularly to make a maximum use of increased winter precipitation. Milder winters might even extend the growing season of some leafy vegetables and *Brassica* species, throughout the whole year in some locations. Contrastingly, the cultivation of determinate crops and cold season species might become increasingly difficult in the warm regions of Germany, especially in summer. Their cultivation might have to be relocated from southern Germany towards the north, or to higher altitudes, with a shift towards warm season crops such as sweet corn and watermelon in the south. These changes will occur because of the following reasons:

- (i) Higher temperatures might cause insufficient cold accumulation in some species. Insufficient vernalization is unfavorable for head formation in cauliflower, but may benefit other species such as lettuce and cabbage, due to reduced incidence of bolting in spring. Milder winters might cause a lack of winter chill in perennials such as asparagus and rhubarb with subsequent reductions in yield.
- (ii) In pea, onion, and other determinate crops, yield reductions might emerge from hastened development at high temperatures, resulting in reduced light interception during the shortened vegetative stage.
- (iii) Heat waves will further reduce crop duration of such species, while yield reductions in fruiting crops e.g. beans might result from reduced fruit set.

In spite of this, choosing the right cultivar for the right location and season will become more significant for growers, while plant breeders will have to provide the industry with new cultivars of improved tolerance towards heat and drought stress, insufficient

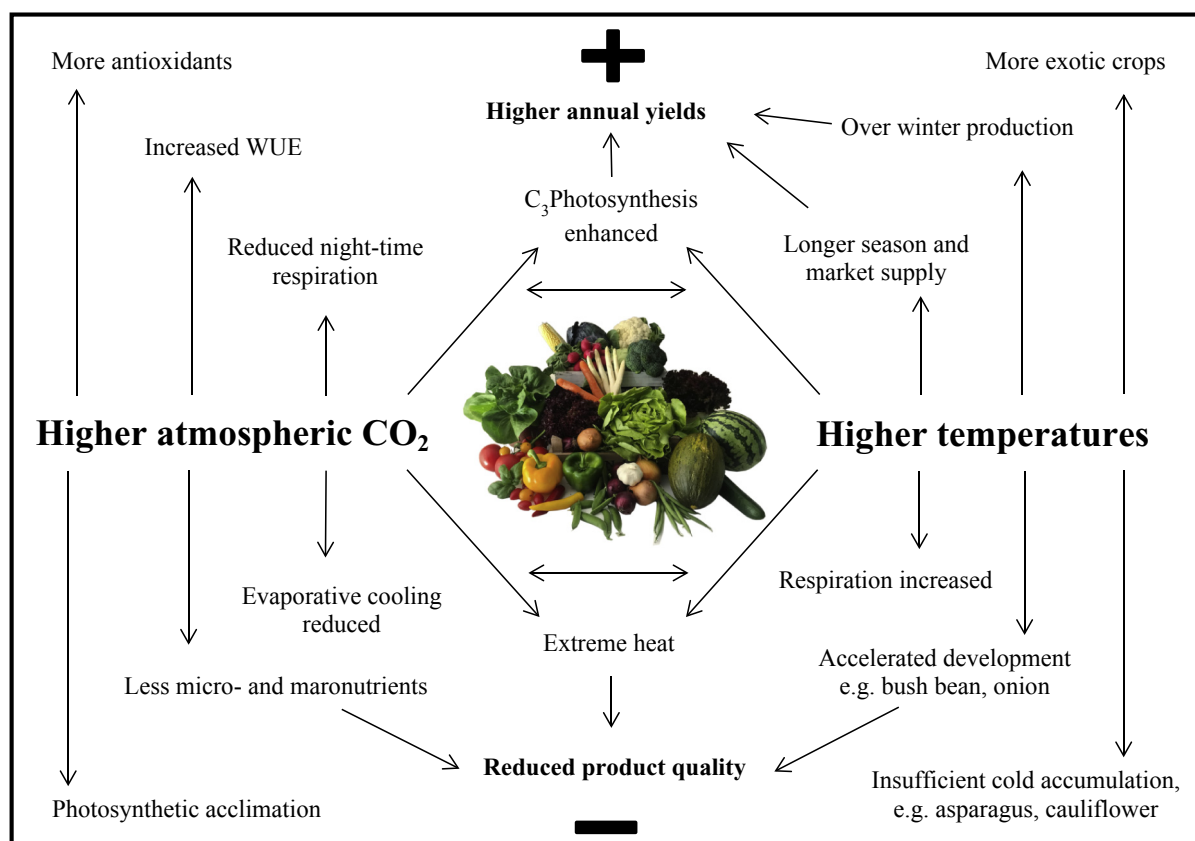


Fig. 3. Climate change will most likely cause higher temperatures and higher atmospheric CO₂ concentrations. Both will have an influence on yield and product quality of vegetables. These influences and interactions can be either positive (+) or negative (-). (Photo: Bisbis and Teixeira, private collection).

chilling and vernalization, hastened development, and with an extended shelf life.

It is also expected that pest and disease infestations will become more intense with new species emerging, thereby requesting more effective plant protection measures. The use of insect nets might have to expand with an overall shift towards more protected cultivation. Future research should include more studies on how climate change affects physiology and population dynamics of the common vegetable pests, their interactions with plants as well as the development of cultivars with greater resistances.

It is difficult to comprehend how vegetable product quality will develop in future scenarios due to the complexity of this topic. Accelerating phenology may alter appearance, for instance puffy lettuce heads, while heat waves can reduce external quality in bean, pea or sweet corn. Unless adaptations are implemented, it is more probable that product quality is going to diminish as a result of lower fruit carotenoid contents at high temperatures, lower macro- and micronutrients content at high CO₂ concentrations and an increased occurrence of sunburn and physiological disorders. However, antioxidant capacity might be higher when exposed to high irradiance e.g. in tomato, and elevated CO₂ e.g. in lettuce and spinach, thus there are also opportunities to improve product quality. This can be achieved by further investigating new cultivation methods such as shading of field vegetables in temperate regions, in order to reduce excessive radiation and heat built up and avoid losses of product quality, while for the quality degradation at high CO₂ in terms of macro- and micronutrients, breeding might be the only solution to date. If these adaptations are realized, it might be possible to produce higher vegetable yields of better internal quality while securing external quality, which reduces production risks, waste, and makes the vegetable sector economically more rewarding. In Fig. 3 we provide a summary of the most important climate change impacts included in this paper, with their positive and negative outcomes.

In greenhouses the high relative humidity in winter might become increasingly problematic in the future while in summer the main problem will be coping with excessive heat and irradiation during heat waves. There is a broad range of technical tools that may be useful in dealing with this, for instance air treatment units or evaporative cooling. Shading is common practice but the length of the shading period is increasing; quality reductions due to low irradiation have been shown to result from permanent shading (Gruda and Tanny, 2014). Furthermore, there should be government plans to aid growers modernize their old greenhouse constructions, which are still widely used in Germany, in order to ensure effective climate control and maintain good product quality.

Precipitation patterns are expected to shift, with long periods of summer drought that will increase the competition between water users. Thus efficient water supply must be secured, and the vegetable production sector will have to come up with innovative solutions such as drip irrigation, soil mulching, aquifer management, and water reservoirs. Contrarily, excessive soil moisture, due to more rainfall in seasons other than summer must be avoided by using drainage systems combined with water storage. The maintenance and modernization of such systems becomes increasingly important in providing a proper drainage function.

Implementing innovative adaptations could enable vegetable producers to mitigate the adverse effects of climate change, while profiting from higher annual yields due to the extended growing season and elevated CO₂ as well as from higher antioxidant capacity under slightly stressed conditions. This can only be achieved by using innovative technology, by a more efficient use of water resources and by the use of renewable energy sources. Thereby, the sustainability of future horticulture will be secured, waste products minimized and high food security standards maintained, so that

future generations may also benefit from the consumption of fresh, and healthy vegetables.

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References

- Abdelmageed, A.H.A., Gruda, N., 2007. Influence of heat shock pretreatment on growth and development of tomatoes under controlled heat stress conditions. *J. Appl. Bot. Food Qual.* 81 (1), 26–28.
- Abdelmageed, A.H.A., Gruda, N., 2009a. Influence of grafting on growth, development and some physiological parameters of tomatoes under controlled heat stress conditions. *Eur. J. Hort. Sci.* 16–20.
- Abdelmageed, A.H.A., Gruda, N., 2009b. Influence of high temperatures on gas exchange rate and growth of eight tomato cultivars under controlled heat stress conditions. *Eur. J. Hort. Sci.* 152–159.
- Agüera, E., Ruano, D., Cabello, P., de la Haba, P., 2006. Impact of atmospheric CO₂ on growth, photosynthesis and nitrogen metabolism in cucumber (*Cucumis sativus* L.) plants. *J. Plant Physiol.* 163 (8), 809–817.
- Aleixandre-Benavent, R., Aleixandre-Tudó, J.L., Castelló-Cogollos, L., Aleixandre, J.L., 2017. Trends in scientific research on climate change in agriculture and forestry subject areas (2005–2014). *J. Clean. Prod.* 147, 406–418.
- Allakhverdiev, S.I., Kreslavski, V.D., Klimov, V.V., Los, D.A., Carpentier, R., Mohanty, P., 2008. Heat stress: an overview of molecular responses in photosynthesis. *Photosynth. Res.* 98 (1–3), 541–550.
- Altunlu, H., Gul, A., 2012. Increasing drought tolerance of tomato plants by grafting. In: *V Balkan Symposium on Vegetables and Potatoes*, vol. 960, pp. 183–190.
- Ayyogari, K., Sidhya, P., Pandit, M.K., 2014. Impact of climate change on vegetable cultivation—a review. *Int. J. Agric. Environ. Biotechnol.* 7 (1), 145.
- Bagley, J., Rosenthal, D.M., Ruiz-Vera, U.M., Siebers, M.H., Kumar, P., Ort, D.R., Bernacchi, C.J., 2015. The influence of photosynthetic acclimation to rising CO₂ and warmer temperatures on leaf and canopy photosynthesis models. *Glob. Biogeochem. Cycles* 29 (2), 194–206.
- Becker, C., Kläring, H.P., 2016. CO₂ enrichment can produce high red leaf lettuce yield while increasing most flavonoid glycoside and some caffeic acid derivative concentrations. *Food Chem.* 199, 736–745.
- Beckerson, D.W., Hofstra, G., 1979. Response of leaf diffusive resistance of radish, cucumber and soybean to O₃ and SO₂ singly or in combination (1967). *Atmos. Environ.* 13 (9), 1263–1268.
- Ben-Asher, J., y Garcia, A.G., Hoogenboom, G., 2008. Effect of high temperature on photosynthesis and transpiration of sweet corn (*Zea mays* L. var. *rugosa*). *Photosynthetica* 46 (4), 595–603.
- Berthold, C., 2009. Securing irrigated agricultural production under climate change (in German). In: *Integriertes Klimaschutzprogramm Hessen INKLIM 2012 II Plus (Abschlussbericht)*, Hessen, Germany.
- Bettoni, M.M., Mogor, A.F., Pualetti, V., Goicoechea, N., 2014. Growth and metabolism of onion seedlings as affected by the application of humic substances, mycorrhizal inoculation and elevated CO₂. *Sci. Hort.* 180, 227–235.
- Blanke, M.M., Burdick, B., 2005. Food (miles) for thought — energy balance for locally-grown versus imported apple fruit. *Environ. Sci. Pollut. Res.* 12 (3), 125–127.
- Blanke, M.M., Huckleby, D.P., Notton, B.A., Lenz, F., 1987. Utilization of bicarbonate by apple fruit phosphoenolpyruvate carboxylase. *Phytochemistry* 26 (9), 2475–2476.
- Blanke, M.M., Kunz, A., 2010. Effects of climate change on pome fruit phenology and precipitation. In: *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on*, vol. 922, pp. 381–386.
- Boersma, M., Gracie, A.J., Brown, P.H., 2009. Relationship between growth rate and the development of hollow stem in broccoli. *Crop Pasture Sci.* 60 (10), 995–1001.
- Booker, F., Muntifering, R., McGrath, M., Burkey, K., Decoteau, D., Fiscus, E., Grant, D., 2009. The ozone component of global change: potential effects on agricultural and horticultural plant yield, product quality and interactions with invasive species. *J. Integr. Plant Biol.* 51 (4), 337–351.
- Burkey, K.O., Booker, F.L., Ainsworth, E.A., Nelson, R.L., 2012. Field assessment of a snap bean ozone bioindicator system under elevated ozone and carbon dioxide in a free air system. *Environ. Pollut.* 166, 167–171.
- Buttaro, D., Santamaria, P., Signore, A., Cantore, V., Boari, F., Montesano, F.F., Parente, A., 2015. Irrigation management of greenhouse tomato and cucumber using tensiometer: effects on yield, quality and water use. *Agric. Agric. Sci. Procedia* 4, 440–444.
- Butterly, C.R., Armstrong, R., Chen, D., Tang, C., 2016. Free-air CO₂ enrichment (FACE) reduces the inhibitory effect of soil nitrate on N₂ fixation of *Pisum sativum*. *Ann. Bot.* 117 (1), 177–185.
- Calvo, E., Martin, C., Sanz, M., 2007. Ozone sensitivity differences in five tomato cultivars: visible injury and effects on biomass and fruits. *Water Air Soil Pollut.* 186, 167–181.
- Chmielewski, F.M., 2007. Impacts of climate change on agriculture and forestry. In:

- Klimawandel-Einblicke, Rückblicke und Ausblicke-. Humboldt Universität zu Berlin, Germany, pp. 75–86 (In German).
- Choi, E.Y., Seo, T.C., Lee, S.G., Cho, I.H., Stangoulis, J., 2011. Growth and physiological responses of Chinese cabbage and radish to long-term exposure to elevated carbon dioxide and temperature. *Hortic. Environ. Biotechnol.* 52 (4), 376–386.
- Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., Richels, R., 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Energy, Office of Biological & Environmental Research, Washington, 7 DC., USA, p. 154.
- Conesa, M.A., Galmés, J., Ochogavía, J.M., March, J., Jaume, J., Martorell, A., Francis, D.M., Medrano, H., Jocelyne, K.C.R., Cifre, J., 2014. The postharvest tomato fruit quality of long shelf-life Mediterranean landraces is substantially influenced by irrigation regimes. *Postharvest Biol. Technol.* 93, 114–121.
- Coolong, T.W., Randle, W.M., 2003. Temperature influences flavor intensity and quality in granex 33'Onion. *J. Am. Soc. Hortic. Sci.* 128 (2), 176–181.
- Da Matta, F.M., Grandis, A., Arenque, B.C., Buckeridge, M.S., 2009. Impacts of climate changes on crop physiology and food quality. *Food Res. Int.* 43 (7), 1814–1823.
- Däder, B., Fereres, A., Moreno, A., Trebicki, P., 2016. Elevated CO₂ impacts bell pepper growth with consequences to *Myzus persicae* life history, feeding behaviour and virus transmission ability. *Sci. Rep.* 6.
- Daymond, A.J., Wheeler, T.R., Hadley, P., Ellis, R.H., Morison, J.I.L., 1997. The growth, development and yield of onion (*Allium cepa* L.) in response to temperature and CO₂. *J. Hortic. Sci. (U. K.)*.
- De Bock, M., Ceulemans, R., Horemans, N., Guisez, Y., Vandermeiren, K., 2012. Photosynthesis and crop growth of spring oilseed rape and broccoli under elevated tropospheric ozone. *Environ. Exp. Bot.* 82, 28–36.
- De la Peña, R., Hughes, J., 2007. Improving vegetable productivity in a variable and changing climate. *J. SAT Agric. Res.* 4 (1), 1–22.
- Dietrich, O., Schubert, U., Schubert, J., Steidl, J., Zander, P., 2015. Report: Water-management in Agriculture. Bundesanstalt für Landwirtschaft und Ernährung, Bonn (in German).
- Ebel, R., 2015. What climate change means for irrigation. *Gemüse* 10, 24–25 (in German).
- Edwards, G., Walker, D., 1983. C₃ C₄: Mechanisms, and Cellular and Environmental Regulations of Photosynthesis. Blackwell Scientific Publications, Oxford, London, Edinburgh, Boston, Melbourne.
- Elings, A., Kempkes, F.L.K., Kaarsemaker, R.C., Ruijs, M.N.A., Van de Braak, N.J., Dueck, T.A., 2005. The energy balance and energy-saving measures in greenhouse tomato cultivation. In: *Int. Conf. Sustain. Greenh. Syst.* 691, 67–74.
- Ernst, M., 2012. Climate change and vegetable production in the upper Rhine rift. In: *Der Oberrheingraben im Klimawandel eine Region passt sich an. Regionalkonferenz des Bundes und der Länder Baden-Württemberg, Hessen und Rheinland-Pfalz*, pp. 51–52 (in German).
- Farneti, B., Schouten, R.E., Qian, T., Dieleman, J.A., Tijssens, L.M.M., Woltering, E.J., 2013. Greenhouse climate control affects postharvest tomato quality. *Postharvest Biol. Technol.* 86, 354–361.
- Feller, C., Jaworski, H., 2016. Macro- and micronutrient deficiency in asparagus. *Gemüse* 4, 16–19 (in German).
- Fink, M., Kläring, H.P., George, E., 2009. Horticulture and climate change. In: *Dirksmayer, W., Sourell, H. (Eds.), Water in Horticulture*, vol. 328. Landbauforschung, Sdh, pp. 1–9 (in German).
- Flaig, H., 2013. Adaptations to Climate Change in Baden-Württemberg. Expert Assessment for Field of Action in Horticulture Part a. Landwirtschaftliches Technologiezentrum Augustenberg, Karlsruhe long version (in German).
- Flowers, M.D., Fiscus, E.L., Burkey, K.O., Booker, F.L., Dubois, J.J.B., 2007. Photosynthesis, chlorophyll fluorescence, and yield of snap bean (*Phaseolus vulgaris* L.) genotypes differing in sensitivity to ozone. *Environ. Exp. Bot.* 61, 190–198.
- Fuhrer, J., 2003. Agroecosystem responses to combinations of elevated CO₂, ozone, and global climate change. *Agric. Ecosyst. Environ.* 97 (1), 1–20.
- Fujino, J., Nair, R., Kainuma, M., Masui, T., Matsuo, Y., 2006. Multi-gas mitigation analysis on stabilization scenarios using AIM global model. *Energy* J. 343–353.
- Giri, A., Armstrong, B., Rajashekar, C.B., 2016. Elevated carbon dioxide level suppresses nutritional quality of lettuce and spinach. *Am. J. Plant Sci.* 7 (1), 246.
- Gómez, C., Mitchell, C.A., 2013. Supplemental lighting for greenhouse-grown tomatoes: intracanopy led towers vs. overhead HPS lamps. In: *International symposium on new technologies for environment control. Energy-Saving Crop Prod. Greenh. Plant* 1037, 855–862.
- Goudriaan, J., Bijlsma, R.J., 1987. Effect of CO₂ enrichment on growth of Faba beans at two levels of water supply. *Neth. J. Agric. Sci.* 35, 189–191.
- Grange, R.I., Hand, D.W., 1987. A review of the effects of atmospheric humidity on the growth of horticultural crops. *J. Hortic. Sci.* 62 (2), 125–134.
- Gruda, N., 2005. Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. *Crit. Rev. Plant Sci.* 24 (3), 227–247.
- Gruda, N., 2009. Do soilless culture systems have an influence on product quality of vegetables? *J. Appl. Bot. Food Qual.* 82, 141–147.
- Gruda, N., Heine, H., 2002. Hollow stems in broccoli – a cultivar issues as well? *Gemüse* 38 (8), 13–14 (in German).
- Gruda, N., Tanny, J., 2014. Protected crops. In: *Dixon, G.R., Aldous, D.E. (Eds.), Horticulture: Plants for People and Places*, vol. 1. Springer, Netherlands, pp. 327–405.
- Gruda, N., Tanny, J., 2015. Protected crops – recent advances, innovative technologies and future challenges. In: *The 29th International Horticultural Congress in Brisbane, Australia, 17–22 August 2014*, vol. 107. Acta Hort, pp. 271–277.
- Gutbrodt, B., Mody, K., Dorn, S., 2011. Drought changes plant chemistry and causes contrasting responses in lepidopteran herbivores. *Oikos* 120 (11), 1732–1740.
- Hand, D.W., 1988. Effects of atmospheric humidity on greenhouse crops. In: *Symposium on Biological Aspects of Energy Saving in Protected Cultivation*, vol. 229, pp. 143–158.
- Hijioka, Y., Matsuo, Y., Nishimoto, H., Masui, M., Kainuma, M., 2008. Global GHG emissions scenarios under GHG concentration stabilization targets. *J. Glob. Environ. Eng.* 13, 97–108.
- Hoffmann, H., Rath, T., 2009. Inter-regional simulations of future energy consumption in greenhouses under IPCC-scenarios. In: *GIL Jahrestagung*, pp. 61–64 (in German).
- Hribar, J., Vidrih, R., 2015. Impacts of climate change on fruit physiology and quality. In: *Proceedings. 50th Croatian and 10th International Symposium on Agriculture. Opatija, Croatia*, vol. 42, p. 45.
- Hullé, M., d'Acier, A.C., Bankhead-Dronnet, S., Harrington, R., 2010. Aphids in the face of global changes. *Comptes Rendus Biol.* 333 (6), 497–503.
- Ibrahim, M.A., Nissinen, A., Prozhnerina, N., Oksanen, E.J., Holopainen, J.K., 2006. The influence of exogenous monoterpene treatment and elevated temperature on growth, physiology, chemical content and headspace volatiles of two carrot cultivars (*Daucus carota* L.). *Environ. Exp. Bot.* 56 (1), 95–107.
- IPCC, 2000. Summary for policymakers. In: *Nakicenovic, Nebojsa, Davidson, Ogunlade, Davis, Gerald, Grubler, Arnulf, Kram, Tom, La Rovere, Emilio Lebre, Metz, Bert (Eds.), Emissions Scenarios: a Special Report of IPCC Working Group III*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2007. Summary for policymakers. In: *climate change 2007: the physical science basis*. In: *Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2013. Summary for policymakers. In: *climate change 2013: the physical science basis*. In: *Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jacob, D., Göttel, H., Kotlarsky, S., Lorenz, P., Sieck, K., 2008. Impacts of Climate Change and Adaptation in Germany - Phase 1: Developing Climate Scenarios for Germany. Umweltbundesamt, Dessau-Roßlau, Germany (in German).
- Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Georgopoulou, E., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg. Environ. Change* 14 (2), 563–578.
- Jahnke, S., 2001. Atmospheric CO₂ concentration does not directly affect leaf respiration in bean or poplar. *Plant. Cell & Environ.* 24 (11), 1139–1151.
- Jamieson, M.A., Trowbridge, A.M., Raffa, K.F., Lindroth, R.L., 2012. Consequences of climate warming and altered precipitation patterns for plant-insect and multitrophic interactions. *Plant Physiol.* 160 (4), 1719–1727.
- Jin, C., Du, S., Wang, Y., Condon, J., Lin, X., Zhang, Y., 2009. Carbon dioxide enrichment by composting in greenhouses and its effect on vegetable production. *J. Plant Nutr. Soil Sci.* 172 (3), 418–424.
- Kalużewicz, A., Krzesiński, W., Knaflowski, M., 2009. Effect of temperature on the yield and quality of broccoli heads. *Veg. Crops Res. Bull.* 71, 51–58.
- Keatinge, J.D.H., Ledesma, D.R., Keatinge, F.J.D., Hughes, J.A., 2012. Projecting annual air temperature changes to 2025 and beyond: implications for vegetable production worldwide. *J. Agric. Sci.* 152 (1), 38–57.
- Körner, C., 2006. Significance of temperature in plant life. In: *Morison, J.I.L., Morecroft, M.D. (Eds.), Plant Growth and Climate Change*. Blackwell, Oxford, UK, pp. 48–70.
- Korres, N.E., Norsworthy, J.K., Tehranchian, P., Gitsopoulos, T.K., Loka, D.A., Oosterhuis, D.M., ..., Palhano, M., 2016. Cultivars to face climate change effects on crops and weeds: a review. *Agron. Sustain. Dev.* 36 (1), 1–22.
- Kyei-Boahen, S., Astatkie, T., Lada, R., Gordon, R., Caldwell, C., 2003. Gas exchange of carrot leaves in response to elevated CO₂ concentration. *Photosynthetica* 41 (4), 597–603.
- Laber, H., Lattauschke, G., 2014. Vegetable Production, 2. Edition. Eugen Ulmer Verlag, Stuttgart, Germany (In German).
- Lattauschke, G., 2015a. Significant differences in early onion cultivars at difficult growth conditions. In: *Versuche im deutschen Gartenbau 2015. Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, Dresden* (in German).
- Lattauschke, G., 2015b. Extreme heat caused massive yield and quality reductions in medium and late peas. In: *Versuche im deutschen Gartenbau 2015. Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie, Dresden* (in German).
- Leakey, A.D., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., Ort, D.R., 2009. Elevated CO₂ effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *J. Exp. Bot.* 60 (10), 2859–2876.
- Li, Z., Palmer, W.M., Martin, A.P., Wang, R., Rainsford, F., Jin, Y., Ruan, Y.L., 2012. High invertase activity in tomato reproductive organs correlates with enhanced sucrose import into, and heat tolerance of, young fruit. *J. Exp. Bot.* 63 (3), 1155–1166.
- Lin, D., Xia, J., Wan, S., 2010. Climate warming and biomass accumulation of terrestrial plants: a meta-analysis. *New Phytol.* 188 (1), 187–198.
- Lin, K.H., Huang, M.Y., Huang, W.D., Hsu, M.H., Yang, Z.W., Yang, C.M., 2013. The

- effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. *capitata*). *Sci. Hortic.* 150, 86–91.
- Lindemann-Zutz, K., Fricke, A., Stützel, H., 2016. Prediction of time to harvest and its variability in broccoli (*Brassica oleracea* var. *italica*) Part I. Plant developmental variation and forecast of time to head induction. *Sci. Hortic.* 198, 424–433.
- Luedeling, E., Guo, L., Dai, J., Leslie, C., Blanke, M.M., 2013b. Differential responses of trees to temperature variation during the chilling and forcing phases. *Agric. For. Meteorol.* 181, 33–42.
- Luedeling, E., Kunz, A., Blanke, M.M., 2013a. Effect of recent climate change on cherry phenology. *Int. J. Biometeorol.* 57, 679–689.
- Martineau, V., Lefsrud, M., Naznin, M.T., Kopsell, D.A., 2012. Comparison of light-emitting diode and highpressure sodium light treatments for hydroponics growth of Boston lettuce. *HortScience* 47 (4), 477–482.
- Mattos, L.M., Moretti, C.L., Jan, S., Sargent, S.A., Lima, C.E.P., Fontenelle, M.R., 2014. Climate changes and potential impacts on quality of fruit and vegetable crops. *Emerg. Technol. Manag. Crop Stress Toler.* 1, 467–486.
- Mauzerall, D.L., Wang, X., 2001. Protecting agricultural crops from the effects of tropospheric ozone exposure: reconciling science and standard setting in the United States, Europe, and Asia. *Annu. Rev. Energy Environ.* 26 (1), 237–268.
- Mølmann, J.A., Steindal, A.L., Bengtsson, G.B., Seljåsen, R., Lea, P., Skaret, J., Johansen, T.J., 2015. Effects of temperature and photoperiod on sensory quality and contents of glucosinolates, flavonols and vitamin C in broccoli florets. *Food Chem.* 172, 47–55.
- Moretti, C.L., Mattos, L.M., Calbo, A.G., Sargent, S.A., 2010. Climate changes and potential impacts on postharvest quality of fruit and vegetable crops: a review. *Food Res. Int.* 43 (7), 1824–1832.
- Moriondo, M., Bindu, M., Kundzewicz, Z.W., Szwed, M., Chorynski, A., Matczak, P., Wreford, A., 2010. Impact and adaptation opportunities for European agriculture in response to climatic change and variability. *Mitig. Adapt. Strat. Glob. Change* 15 (7), 657–679.
- Nie, L.C., Chen, Y.H., Liu, M., 2016. Effects of low temperature and chilling duration on bud break and changes of endogenous hormones of asparagus. *Eur. J. Hort. Sci.* 81 (1), 22–26.
- Olesen, J.E., Bindu, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* 16 (4), 239–262.
- Olle, M., Bender, I., 2009. Causes and control of calcium deficiency disorders in vegetables: a review. *J. Hortic. Sci. Biotechnol.* 84 (6), 577–584.
- Oshima, R.J., Taylor, O.C., Braegelman, P.K., Baldwin, D.W., 1975. Effect of ozone on the yield and plant biomass of a commercial variety of tomato. *J. Environ. Qual.* 4 (4), 463–464.
- Peet, M.M., 1986. Acclimation to high CO₂ in monoecious cucumbers I. Vegetative and reproductive growth. *Plant Physiol.* 80 (1), 59–62.
- Peet, M.M., Wolfe, D.W., 2000. Crop ecosystem responses to climatic change: vegetable crops. In: Reddy, K.R., Hodges, H.F. (Eds.), *Climate Change and Global Crop Productivity*. CAB International, Oxon-New York, pp. 213–243.
- Pfeifer, S., Bülow, K., Gobiet, A., Hänslar, A., Mudelsee, M., Otto, J., ..., Jacob, D., 2014. Robustness of ensemble climate projections with climate signal maps: seasonal and extreme precipitation for Germany. *Atmosphere* 6 (5), 677–698.
- Porch, T.G., Jahn, M., 2001. Effects of high-temperature stress on microsporogenesis in heat-sensitive and heat-tolerant genotypes of *Phaseolus vulgaris*. *Plant, Cell & Environ.* 24 (7), 723–731.
- Potop, V., Koudela, M., Mozy, M., Ustas, C.H., 2011. The Impact of Dry, Wet and Heat Episodes on the Production of Vegetable Crops in Polabí (River Basin). *Scientia Agriculturae Bohemica, Czech Republic*.
- Potop, V., Zahradníček, P., Tůrkott, L., Štěpánek, P., Soukup, J., 2014. Potential impacts of climate change on damaging frost during growing season of vegetables. *Sci. Agric. Bohem.* 45 (1), 26–35.
- Prasad, P.V., Boote, K.J., Allen, L.H., Thomas, J.M., 2002. Effects of elevated temperature and carbon dioxide on seed-set and yield of kidney bean (*Phaseolus vulgaris* L.). *Glob. Change Biol.* 8 (8), 710–721.
- Radoglou, K.M., Aphalo, P., Jarvis, P.G., 1992. Response of photosynthesis, stomatal conductance and water use efficiency to elevated CO₂ and nutrient supply in acclimated seedlings of *Phaseolus vulgaris* L. *Ann. Bot.* 70 (3), 257–264.
- Reich, M., Meerakker, A.N., Parmar, S., Hawkesford, M.J., De Kok, L.J., 2015. Temperature determines size and direction of effects of elevated CO₂ and nitrogen form on yield quantity and quality of Chinese cabbage. *Plant Biol.* 18 (S1), 63–75.
- Riahi, K., Nakicenovic, N., 2007. Greenhouse gases – integrated assessment, technological forecasting and social change. *Special Issue. ISSN: 0040-1625*, 74 (7), 234. September 2007.
- Rosales, M.A., Cervilla, L.M., Sánchez-Rodríguez, E., Rubio-Wilhelmi, M.D.M., Blasco, B., Rios, J.J., ..., Ruiz, J.M., 2010. The effect of environmental conditions on nutritional quality of cherry tomato fruits: evaluation of two experimental Mediterranean greenhouses. *J. Sci. Food Agric.* 91 (1), 152–162.
- Rosenfeld, H.J., Samuelsen, R.T., Lea, P., 1998. The effect of temperature on sensory quality, chemical composition and growth of carrots (*Daucus carota* L.) I. Constant diurnal temperature. *J. Hortic. Sci. Biotechnol.* 73 (2), 275–288.
- Ruhm, G., Gruda, N., Bokelmann, W., Schmidt, U., 2009. The effect of price increases of heating oil on horticultural companies in Saxony. Part II: measures for saving energy costs in glasshouse companies (2). In: *Berichte über Landwirtschaft. Band, vol. 87*, pp. 87–105 (in German).
- Ruiz-Vera, U.M., Siebers, M.H., Drag, D.W., Ort, D.R., Bernacchi, C.J., 2015. Canopy warming causes photosynthetic acclimation and reduced seed yield in maize grown at ambient and elevated [CO₂]. *Glob. Change Biol.* 21 (11), 4237–4249.
- Sage, R.F., Sharkey, T.D., Seemann, J.R., 1989. Acclimation of photosynthesis to elevated CO₂ in five C₃ species. *Plant Physiol.* 89 (2), 590–596.
- Saha, S., Kalia, P., Sureja, A.K., Sarkar, S., 2016. Breeding tropical carrots (*Daucus carota*) for enhanced nutrition and high temperature stress. *Indian J. Agric. Sci.* 86 (7).
- Sánchez-Guerrero, M.C., Lorenzo, P., Medrano, E., Castilla, N., Soriano, T., Baille, A., 2005. Effect of variable CO₂ enrichment on greenhouse production in mild winter climates. *Agric. For. Meteorol.* 132 (3), 244–252.
- Sato, S., Peet, M.M., Thomas, J.F., 2000. Physiological factors limit fruit set of tomato (*Lycopersicon esculentum* Mill.) under chronic, mild heat stress. *Plant, Cell & Environ.* 23 (7), 719–726.
- Saure, M.C., 1998. Causes of the tipburn disorder in leaves of vegetables. *Sci. Hortic.* 76, 131–147.
- Schneider, R., 2016. Irrigation more than ever! Gemüse 3, 22–23 (in German).
- Shahak, Y., 2008. Photo-selective netting for improved performance of horticultural crops. A review of ornamental and vegetable studies carried out in Israel. In: XXVII International Horticultural Congress- IHC2006: International Symposium on Cultivation and Utilization of Asian, vol. 770. *Acta Hort*, pp. 161–168.
- Siddique, M.A., Goodwin, P.B., 1980. Seed vigour in bean (*Phaseolus vulgaris* L. cv. Apollo) as influenced by temperature and water regime during development and maturation. *J. Exp. Bot.* 31 (1), 313–323.
- Solomakhin, A., Blanke, M., 2010. The microclimate under colored hailnets affects leaf and fruit temperature, leaf anatomy, vegetative and reproductive growth as well as fruit coloration in apple. *Ann. Appl. Biol.* 156 (1), 121–136.
- Taiz, L., Zeiger, E., 2014. *Plant Physiology*, sixth ed. SAGE Publications Inc, Los Angeles, London, New Delhi, Singapur, Washington D.C., USA.
- Tantau, H.J., Achilles, W., Schmidt, U., Dannehl, D., Schuch, I., Rocks, T., ..., Bredenbeck, H., 2015. Low Energy Greenhouses Results from the ZINEG Project. KTBL, Darmstadt, Germany (in German).
- Tartachnyk, I.I., Blanke, M.M., 2007. Photosynthesis and transpiration of tomato and CO₂ fluxes in a greenhouse under changing environmental conditions in winter. *Ann. Appl. Biol.* 150 (2), 149–156.
- Teichert, A., 2009. Open field drip irrigation in horticulture? In: Dirksmeyer, W., Sourell, H. (Eds.), *Wasser im Gartenbau Tagungsband zum Statusseminar am 9. und 10. Februar 2009*. Johann Heinrich von Thünen-Institut, Braunschweig, pp. 33–37 (in German).
- Temple, P.J., Taylor, O.C., Benoit, L.F., 1986. Yield response of head lettuce (*Lactuca sativa* L.) to ozone. *Environ. Exp. Bot.* 26 (1), 53–58.
- Toivonen, P.M., Hodges, D.M., 2011. Abiotic Stress in Harvested Fruits and Vegetables. *Abiotic Stress in Plants-Mechanisms and Adaptations*. InTech, China, pp. 39–58.
- Van Damme, V., Berkvens, N., Moerkens, R., Berckmoes, E., Wittemans, L., De Vis, R., ..., De Clercq, P., 2014. Overwintering potential of the invasive leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: gelechiidae) as a pest in greenhouse tomato production in Western Europe. *J. Pest Sci.* 88 (3), 533–541.
- Van de Perre, E., Jaxsens, L., Liu, C., Devlieghere, F., De Meulenaer, B., 2014. Climate impact on *Alternaria* moulds and their mycotoxins in fresh produce: the case of the tomato chain. *Food Res. Int.* 68, 41–46.
- Van Vuuren, D.P., Den Elzen, M.G., Lucas, P.L., Eickhout, B., Strengers, B.J., Van Ruijven, B., ..., van Hout, R., 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim. Change* 81 (2), 119–159.
- Vandermeiren, K., De Bock, M., Horemans, N., Guisez, Y., Ceulemans, R., De Temmerman, L., 2012. Ozone effects on yield quality of spring oilseed rape and broccoli. *Atmos. Environ.* 47, 76–83.
- Vanhassel, P., Bleyaert, P., Van Lommel, J., Vandeveld, I., Crappé, S., Van Hese, N., Hanssens, J., Steppe, K., Van Labeke, M.-C., 2015. Rise of nightly air humidity as a measure for tipburn prevention in hydroponic cultivation of butterhead lettuce. *Acta Hortic.* 1107, 195–202.
- Wang, Y., Frei, M., 2011. Stressed food—The impact of abiotic environmental stresses on crop quality. *Agric. Ecosyst. Environ.* 141 (3), 271–286.
- Wheeler, T.R., Hadley, P., Ellis, R.H., Morison, J.I.L., 1993. Changes in growth and radiation use by lettuce crops in relation to temperature and ontogeny. *Agric. For. Meteorol.* 66, 173–186.
- Wiebe, H.J., 1972. Effects of temperature and light on growth and development of cauliflower. IV. Head induction phase (in German). *Gartenbauwiss. – ejhs* 38, 263–280.
- Wien, H.C., 1997. *The Physiology of Vegetable Crops*. Cab International, Oxon-New York.
- Wurr, D.C.E., Edmondson, R.N., Fellows, J.R., 2000. Climate change: a response surface study of the effects of CO₂ and temperature on the growth of French beans. *J. Agric. Sci.* 135 (4), 379–387.
- Wurr, D.C.E., Fellows, J.R., Phelps, K., 1996. Investigating trends in vegetable crop response to increasing temperature associated with climate change. *Sci. Hortic.* 66 (3), 255–263.
- Yamori, W., Noguchi, K.O., Terashima, I., 2005. Temperature acclimation of photosynthesis in spinach leaves: analyses of photosynthetic components and temperature dependencies of photosynthetic partial reactions. *Plant, Cell & Environ.* 28 (4), 536–547.
- Ziska, L.H., Bunce, J.A., 2006. Plant responses to rising atmospheric carbon dioxide. In: Morison, J.I.L., Morecroft, M.D. (Eds.), *Plant Growth and Climate Change*. Oxford: Blackwell, Oxford, UK, pp. 17–47.